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Understanding Natech Accident Scenarios at Carbon Capture and Storage (CCS) Plants

Federica Tamburini[a,*], Federica Ricci[a], Dimitrios Tzioutzios[b], Nicola Paltrinieri[b], Valerio Cozzani[a]

[a]LISES - Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum - Università di Bologna, 40131 Bologna, Italy
[b]Department of Mechanical and Industrial Engineering, NTNU – Norwegian University of Science and Technology, 7034, Trondheim, Norway
federica.tamburini9@unibo.it

Natural hazards hold the potential to impact technological infrastructure, triggering multiple disasters and exposing both the population and the environment at risk. The continuous rise in carbon emissions from anthropogenic activities has led to an escalating climate change crisis, contributing to increased frequency and severity of Natech (Natural Hazard-Triggered Technological Disasters) scenarios. These scenarios pose significant threats to critical infrastructure, including Carbon Capture and Storage (CCS) plants. CCS serves as a crucial short-term decarbonization solution able to combact global warming. However, climate change-related extreme weather events may cause Natech scenarios in CCS facilities, compromising equipment integrity and releasing stored carbon dioxide (CO_2) and other substances. This exacerbates global warming, contaminates flood waters, or induces fire. The intricate link between climate change, Natech events, and resilient CCS infrastructure underscores the importance of climate change mitigation and adaptation strategies. Given the lack of literature regarding Natech scenarios affecting CCS plants, this paper investigates the CCS value chain with the objective of identifying vulnerable components to potential natural events. An inherent safety approach is applied to assess how risk increases considering natural events as potential causes of equipment failure. This study on Natech risks in CCS plants aims to enhance environmental protection, secure critical infrastructure, and foster a resilient, sustainable future.

1. Introduction

In the chemical and process industry, serious accidents can be triggered by natural events impacting process and storage equipment (Cozzani et al., 2010). These kinds of accidents are called Natech (Natural Hazard-Triggered Technological Disasters) scenarios and may lead to extremely severe consequences with respect to human and asset targets, involving equipment damages and hazardous substances releases that cause toxic dispersions, explosions, fires, or environmental contamination (Antonioni et al., 2015). Among all the typologies of natural calamities, an increase in the number of hydro-meteorological events has been observed in the last few years, and their frequency and severity are expected to grow further due to climate change (Cruz and Krausmann, 2013). Considering these premises, it is thus possible that also Natech risk related to flooding may significantly grow in the foreseeable future (Caratozzolo et al., 2022).

At the same time, the interest in climate change is prompting industries and organizations to implement decarbonization technologies aimed at constituting a more environmentally conscious future. Among these innovations, the Carbon Capture and Storage (CCS) strategy represents a promising emissions mitigation method in the prolonged period of the energy transition towards the full replacement of energy fossil fuels (Tamburini et al., 2024). This strategy entails four main steps: (1) Capture, which consists of a set of techniques enabling the separation of released CO_2 from large anthropogenic emitting sources; (2) Conditioning, in which the captured CO_2 stream is processed to achieve the thermodynamic and purity conditions required for the subsequent transport mode; (3) Transport, where CO_2 is conveyed from the capture and conditioning site to the

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storage injection location through rail and road tankers, ships or pipelines; and lastly (4) Storage, which involves the final injection of CO_2 into geologic reservoirs where it is permanently stored (IPCC, 2005). In Figure 1, the CCS value chain process arrangement is schematized.

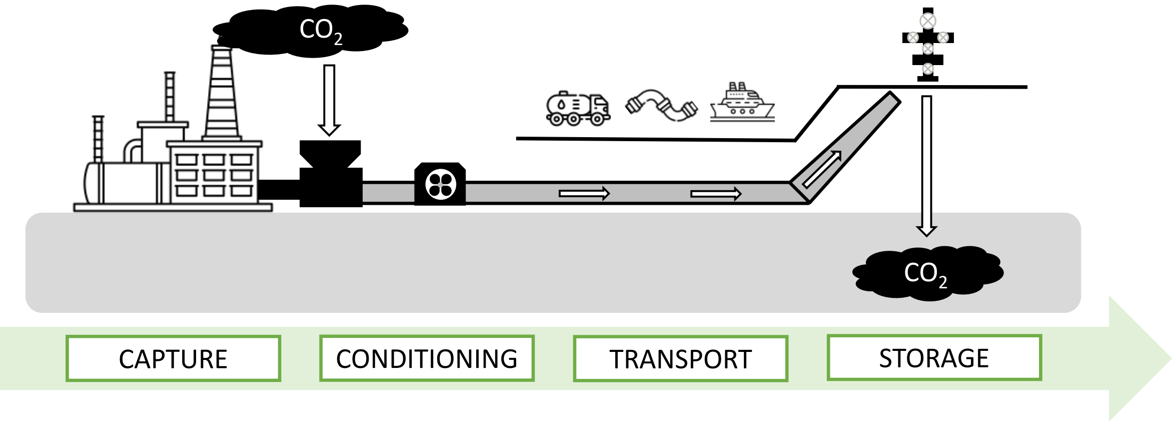

Figure 1: Scheme of the Carbon Capture and Storage (CCS) value chain.

While CCS technology offers a compelling solution to the global warming crisis, its implementation raises concerns regarding the vulnerability of CCS infrastructure to Natech scenarios. Earthquakes, floods, and other natural disasters can pose significant threats to the integrity of CCS systems, potentially threatening their effectiveness in mitigating climate change. As the adoption of CCS technology is gaining momentum, it becomes imperative to investigate and fortify these systems against the unpredictable forces of nature.

Even though many studies discussed the increase in the return period and intensity of natural disasters caused by climate change and investigated chemical and process equipment vulnerabilities to Natech scenarios (Ricci et al., 2021)—to our knowledge—the intricate connection between climate change, Natech scenarios, and resilient CCS infrastructure has never been studied before. Therefore, the present study proposes a novel framework to investigate the CCS value chain and identify vulnerable elements concerning flood and earthquake scenarios. A preliminary consequence assessment is then performed through inherent safety approaches to highlight how natural phenomena impact and tend to increase risk when assumed as causes of equipment failure.

In the following, Section 2 introduces the methodology adopted to assess the inherent safety indexes and Section 3 presents the application of the procedure to a specific notional case study. Then, the results are displayed and discussed in Section 4. Finally, some conclusive remarks are outlined in Section 5.

2. Methodology

The methodology proposed in the current study, schematized in Figure 2, aims to investigate how floods and earthquakes may affect the integrity of CCS equipment and to identify inherent safety indicators in the context of risk assessment. This provides a preliminary view of the increase in damage induced by Natech scenarios on CCS facilities compared to conventional scenarios.

The starting point of the methodology consists of identifying reference flood and seismic conditions, thus establishing the reference events to be analyzed. Each scenario is characterized by a specific intensity and frequency of occurrence. As for the frequency, this can be obtained through the estimation of the return period of a natural event or via the exceedance probability. Focusing on the severity of the scenarios, flood intensity can be defined by means of impact vectors composed of two elements: water depth and water velocity. With regard to earthquakes, specific seismic instrumental parameters for structural applications such as the Peak Ground Acceleration (PGA) or the Peak Ground Velocity (PGV) can be assumed (Lanzano et al., 2014). Clearly enough, the definition of frequency and intensity of a natural event are strictly interconnected. These data are usually available from local authorities through hydrological and geological studies, respectively (Antonioni et al., 2015). Then, the most critical equipment in the CCS system shall be selected based on the available operating conditions. After that, equipment vulnerability models need to be applied to each target item to assess the equipment damage probability and conventional models shall be used to evaluate the consequences of Natech scenarios. Finally, the two inherent safety indices introduced by Tugnoli et al. (2007), the potential hazard index (PI) and the inherent hazard index (HI), are calculated with the aim of providing a preliminary quantification of risk. The PI index represents the effects that may arise from the worst-case accident, providing a rough estimation of the impacted area, while the HI index represents the effects that may result from the worst credible accident, considering the probability of equipment failure (Crivellari et al., 2018). In order to compare indices before and after considering Natech scenarios, an evaluation of the inherent safety with respect to conventional scenarios due to internal failures is also performed.

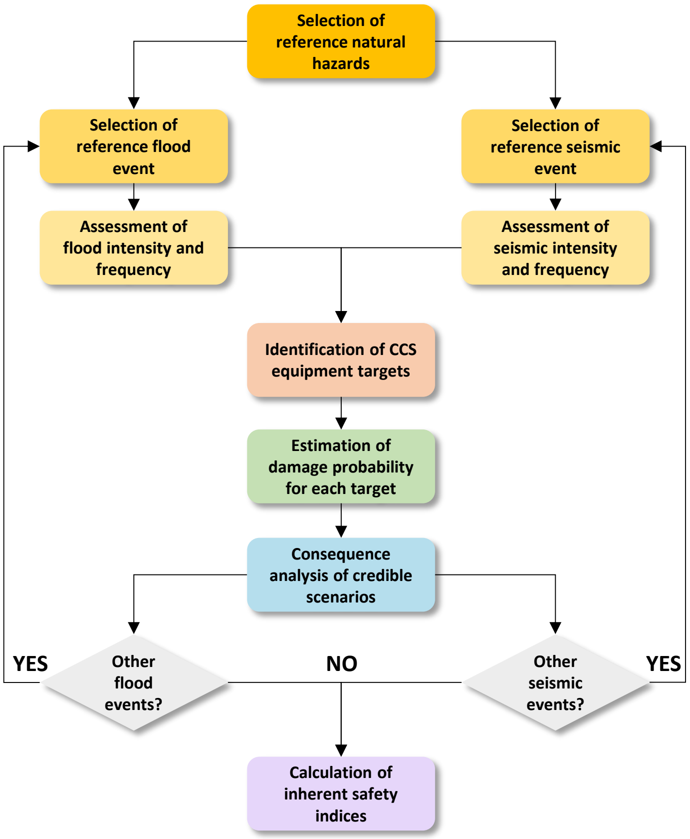

Figure 2: Methodology proposed in the current study.

It is worth noting that the current analysis does not account for domino effects, common escalation scenarios that often follow Natech events (Misuri et al., 2020).

3. Case study

The proposed methodology was applied to a notional case study. It entails a CCS system that involves the capture of CO_2 emissions from the stacks of a thermoelectric plant via an absorption-based Post-Combustion Capture (PCC) process, compression and transport, via pipelines, to a depleted natural gas field where they will be permanently stored. CO_2 is transported in its dense phase; thus, the conditioning stage involves a series of inter-cooled compression, liquefaction, and pumping units working at high pressures and temperatures. These operating conditions make this stage the most critical. Therefore, the equipment items present in the conditioning section of the plant are the target identified through the methodology and are reported in Figure 3.

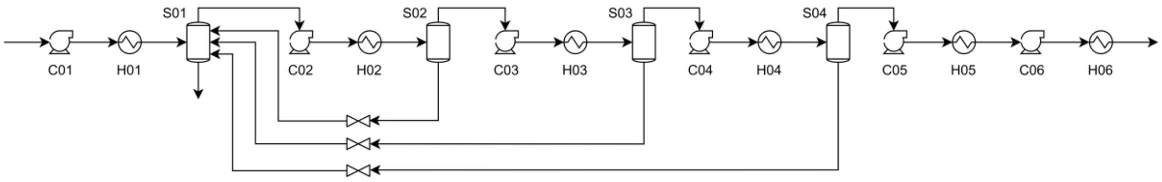

Figure 3: Reference process scheme of the CO_2 conditioning unit considered in the case study (compressors (C), coolers (H), and separators (S)).

Details regarding equipment features are then summarized in Table 1.

Table 1: Main features of the target equipment considered in the case study.

Features	Compressors (C)	Coolers (H)	Separators (S)
Units	6	6	4
Substance	CO_2	CO_2	CO_2
Pressure (bar)	1.8 – 120	3.6 – 120	3.6 – 30
Temperature (°C)	40 – 111.6	40 – 111.6	40
Diameter (m)	/	0.9 – 1.2	5.3 – 9.3
Length/Height (m)	/	7.4 – 9.3	8.4 – 14.3

Table 2 and Table 3 show the flood and seismic reference scenarios, respectively. In the first case (F1) of Table 2, high-depth flood with limited speed is taken into account. On the contrary, in the other cases (F2, F3, and F4) lower severity flood conditions are considered, but characterized by a lower return period and, thus, a higher occurrence frequency. For what concerns earthquakes, a single scenario, whose exceedance probability data are reported in Table 3, is examined.

To estimate the damage probabilities of compressors (C), coolers (H), and separators (S), equipment vulnerability models from Caratozzolo et al. (2022) for floods and from Salzano et al. (2009) for earthquakes are used. In the case of compressor damage in the context of flooding, no vulnerability model is available. In the present study it is assumed that in flood scenarios characterized by relatively lower water heights, the equipment remains undamaged; whereas, in scenarios marked by higher water levels, the equipment fails due to submersion. For more detailed information on the failure modes of the equipment resulting from floods and earthquakes, refer to Cozzani et al. (2010), Khakzad and Van Gelder (2018) and Karagiannakis et al. (2022).

Table 2: Flood reference scenarios considered for the case study.

Flood scenario	Return period (y)	Water depth (m)	Water velocity (m/s)
F1	500	4.2	0.88
F2	100	0.23	0
F3	20	0.30	0
F4	5	0.21	0

Table 3: Seismic exceedance probability data considered for the case study.

Exceedance probability (y^{-1})	PGA (g)
0.01	0.07
0.001	0.36
0.00001	1.31

To perform the consequence analysis, details regarding reference release states and final scenarios must be defined. Since the substance involved in the conditioning unit is CO_2, the only potential scenario arising from the equipment failure is the toxic gas dispersion. Indeed, CO_2 is classified only as a mildly toxic substance (NIOSH, 2007). Also, CO_2 may represent a physical stressors due to the extremely low temperatures it reaches after the release (Tamburini et al., 2023). However, this scenario is not supposed to contribute to any damages, given the rapid sublimation of the small dry ice particles originated following spill events. Furthermore, owing to the characteristics of CO_2, the safety assessment does not account for scenarios involving chemical interactions between the released substance and flood water. Physical effects associated with the final outcome are evaluated by means of PHAST 8.4 software (DNV, 2023) according to conventional procedures (Uijt de Haag and Ale, 1999) and assuming two different safety concentration thresholds for CO_2: the Immediately Dangerous To Life or Health (IDLH), equal to 40,000 ppm (NIOSH, 2007), and the Lethal Concentration (LC50), referred to a death probability of 50 % after inhalation exposure of 30 min, equal to 92,000 ppm (Harper et al., 2011). Based on the assumptions reported in Antonioni et al. (2015) for pressurized vessels (i.e., coolers and separators in the present case study), the release event selected as the most severe due to flooding is the full-bore rupture (FBR) of pipe connections. This event is the most critical also for compressors, as suggested by Salzano et al. (2009). Contrarily, three different reference release modes can be assumed for earthquake-affected separators and coolers: (1) the release from a leak with a diameter of 10 % the nominal diameter of pipe connections (L1); (2) the release from a leak with a diameter of 22 % the nominal diameter of pipe connections (L2); and (3) the FBR of pipe connections. In order to demonstrate the importance of accounting for Natech scenarios in the context of risk assessment, the failure probability due to conventional internal failures is estimated following standard approaches present in Uijt de Haag and Ale (1999). Finally, the last step of the methodology is carried out by estimating the two aformentioned inherent safety indexes for both the damage thresholds considered.

4. Results and discussion

The application of the methodology allows for obtaining the equipment failure frequencies reported in Figure 4. These are consistent across all categories of equipment. Essentially, all equipment items experience failures due to internal damage events for all the considered reference release modes. Floods, however, emerge as a cause of failure only in the case of coolers subjected to the FBR release mode, as indicated by the green bar in the chart. Separators and compressors, instead, are not expected to fail in the case of the flood scenarios considered. Actually, in the case of separators, the critical water velocity does not exceed the reference velocity values reported in Table 2, while for compressors, the water depth is not sufficient to submerge the equipment. In contrast, earthquakes significantly impact all equipment in the conditioning unit. Overall, coolers with pipe connections affected by FBRs exhibit the highest frequency of failure, approximately 0.002 y^{-1}.

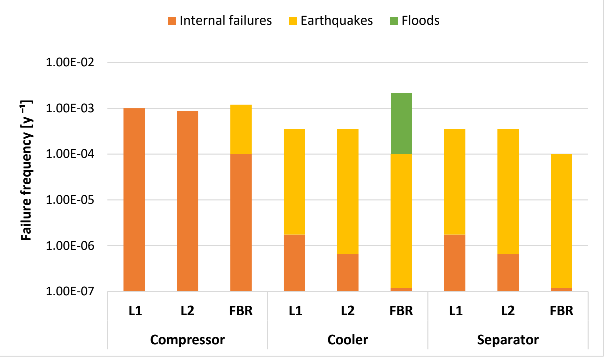

Figure 4: Equipment failure frequency due to internal and external causes for L1, L2, and FBR.

The last step of the methodology involves evaluating the potential and inherent hazard indices, according to the definition provided in Section 2. As obvious, the estimated PI for the IDLH is higher than that associated with the LC50, since the IDLH (40,000 ppm) is lower than the LC50 (92,000 ppm). A PI value of around 10^5 m^2 for the IDLH and a value of 10^4 m^2 for the LC50 are obtained. The same trend can be identified for HI as well, as displayed in Figure 5.

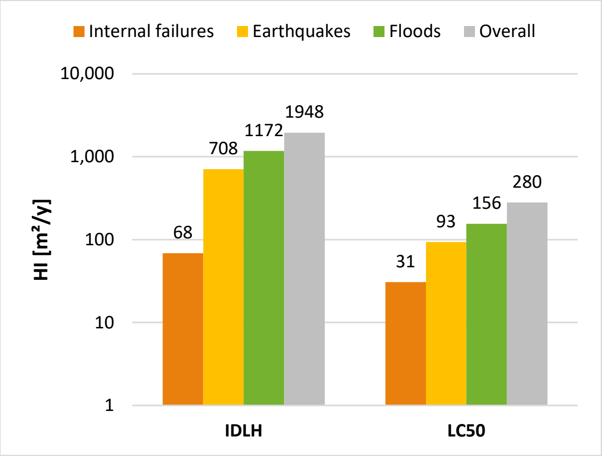

Figure 5: Inherent safety indicator (HI) calculated in correspondence of the IDLH and the LC50.

Based on the definition of PI, it is independent of the failure cause. Thus, no modification in its value occurs when considering additional failure causes, such as natural events. Meanwhile, HI, accounting for the occurrence frequency of failure causes, is influenced by both conventonal and Natech contributions, as depicted in Figure 5. Natech accidents increase the inherent hazard indexes, with flood events impacting more than the seismic activity. For the IDLH damage threshold, Natech accidents raise the conventional HI by about three orders of magnitude. A not negligible increase is also detected for the HI associated with the LC50. In this case, the HI is approximately eight times higher than the conventional one. These findings underscore the importance of considering natural hazards as potential causes of equipment failure in a CCS facility.

5. Conclusions

The current paper explored the impact of natural hazards, specifically floods and earthquakes, on potential accidents within a generic conditioning unit of a CCS plant. The study proposed a novel framework to identify vulnerable components based on equipment failure frequency and evaluated damage distances associated with distinct reference release modes. Subsequently, inherent safety indices were calculated to tangibly assess the impact of natural events on human safety and asset protection. The findings conclusively demonstrated a significant escalation in the probability of CCS conditioning equipment failure due to natural hazards. Recognizing the risk increase introduced by these events is crucial for comprehensive risk management and planning. Integrating considerations of potential Natech accidents becomes essential to comprehend how the overall risk evolves in the presence of such phenomena, diverging from risks solely associated with internal failures. Expanding on this basic framework, future studies may be devoted to applying the proposed methodology to the other sections of the CCS value chain, also including natural events not considered here, in order to obtain a thorough overview of the risks associated with CCS plants. This insight is pivotal for enhancing risk mitigation strategies and ensuring the resilience of CCS systems in the face of diverse challenges.

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