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FAULT TREE ANALYSIS OF A CO_2-EOR INJECTION SYSTEM

Review paper

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Abstract: The application of CO_2 for enhanced oil recovery requires reliable operation of the injection system and the integrity of its technical and geological components. The aim of this study is to systematically identify potential causes and failure events that may lead to the loss of safe and effective CO_2 injection in a CO_2-EOR system. Based on a review of relevant scientific literature and the defined system boundaries, a qualitative Fault Tree Analysis (FTA) model was developed. The top event was divided into two main groups of events: loss of effective injection capability and loss of safe CO_2 containment during injection. The developed model includes surface, wellbore, reservoir, and geomechanical failure pathways, including CO_2 supply and compression problems, corrosion, loss of injectivity, loss of well barrier integrity, and unfavorable reservoir pressure response. The results show that FTA enables different failure mechanisms to be integrated into a structured cause-and-effect model and provides a basis for their further quantitative assessment and prioritization.
Key words: CO_2-EOR, Fault Tree Analysis, injection system, well integrity, failure analysis

INTRODUCTION

The application of CO_2 for enhanced oil recovery (CO_2-EOR) is based on the injection of CO_2 into an oil reservoir to improve oil mobility and increase ultimate oil recovery. In addition to its role in oil production, part of the injected CO_2 may remain stored in the reservoir, which is why CO_2-EOR is also considered in the broader context of reducing carbon dioxide emissions (Novak Mavar et al., 2021).

Safe and effective CO_2 injection depends on the reliable operation of the surface injection system, the maintenance of reservoir injectivity and injection well integrity, and an appropriate geomechanical response of the system.Maintaining the integrity of well barriers is particularly important, as they are exposed to changes in pressure and temperature, as well as chemical and mechanical effects during CO_2 injection (Iyer et al., 2022). The variety of potential failure mechanisms highlights the need for their systematic identification and cause-and-effect analysis.

Fault Tree Analysis (FTA) enables the deductive decomposition of an undesired top event into lower-level events and causes. FTA has previously been applied to identify potential CO_2 leakage pathways and mechanisms in oil reservoirs, with CO_2 leakage considered as the top event (Wang et al., 2020). However, the safe operation of a CO_2-EOR injection system depends not only on preventing leakage, but also on maintaining CO_2 supply and injection capability, reservoir injectivity, and the integrity of technical and geological barriers.

The aim of this study is to systematically identify potential causes and failure events based on published scientific literature and the defined boundaries of the CO_2-EOR injection system, and to develop a qualitative fault tree model for the top event "Loss of Safe and Effective CO_2 Injection in a CO_2-EOR System."

MATERIAL AND METHODS

CO_2-EOR System and Scope of the Analysis

CO_2-EOR is a process in which CO_2 is injected into an oil reservoir to mobilize the remaining oil and increase ultimate oil recovery. Within the broader process chain, CO_2-EOR includes CO_2 supply and preparation, injection into the reservoir, fluid production, surface separation

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and the separation and reinjection of produced CO_2. The produced gas, which mainly consists of CO_2 and associated natural gas, can be reinjected to maintain reservoir pressure, while the broader CO_2-EOR chain covers processes from CO_2 supply and transportation to oil field operations and subsequent handling of the produced oil (Jabbar et al., 2025).
For the purposes of this study, only the part of the system directly related to safe and effective CO_2 injection was analyzed. The system boundary begins with the receipt of CO_2 at the EOR site, i.e., at the end of the transportation system, followed by distribution, additional compression, measurement and control, and delivery of CO_2 to the injection wells. A typical surface injection system at a CO_2-EOR site includes a distribution manifold at the end of the transportation pipeline, distribution pipelines to the wells, additional compression, measurement and control systems, and injection wells (Novak Mavar et al., 2021). The designed injection pressure and flow rate are related to reservoir characteristics and surface facility requirements and are therefore relevant parameters in defining the injection system (Kristanto et al., 2020).
Downstream of the surface facilities, the scope of the analysis includes the injection well and its barriers, including tubing, casing, packer, and cement isolation, as well as the target reservoir and the directly relevant geological containment system. Including these elements makes it possible to consider well integrity, CO_2 injectivity into the reservoir, and the geomechanical response of the system, in addition to CO_2 supply and injection capability. Maintaining well integrity is particularly important during CO_2 injection because injection wells are exposed to changes in pressure and temperature, as well as chemical and mechanical effects that may reduce the effectiveness of well barriers. Tubing, casing, packer, and cement are important components for maintaining injection well integrity (Iyer et al., 2022).
In accordance with the aim of the study, CO_2 capture at the industrial source and the main transportation system upstream of the EOR site were excluded from the FTA, as were production wells, surface separation of produced fluids, recycling of produced CO_2, transportation and processing of crude oil, and its end use. Although these processes are part of the broader CO_2-EOR process chain, their inclusion would extend the analysis beyond the functional scope defined by the top event. Based on these boundaries, the analyzed system includes surface CO_2 supply and injection control, the injection well and its barriers, CO_2 injectivity into the target reservoir, and geomechanical containment, providing the basis for the development of the qualitative FTA model.

Fault Tree Analysis Methodology

A qualitative Fault Tree Analysis (FTA) was applied to systematically organize potential events and cause-and-effect pathways that may lead to the loss of safe and effective CO_2 injection in a CO_2-EOR system. The analysis was based on a review of relevant scientific literature and functional decomposition of the analyzed system.
FTA is a deductive approach to failure analysis that starts with a defined undesired top event and then identifies lower-level events and their logical relationships that may lead to its occurrence (Adamović&Radovanović, 2008; Wang et al., 2020).
After defining the system boundaries, the top event, "Loss of Safe and Effective CO_2 Injection in a CO_2-EOR System," was successively decomposed into lower-level events. The developed model includes the top event (T), intermediate events (G), basic events (P), and undeveloped events (S). Undeveloped events were used when an event was relevant to the analyzed system, but further decomposition was not justified by the available information or the defined scope of the analysis.
The causal relationships between events were represented using logical AND and OR gates. An OR gate was used when the occurrence of any of the input events was sufficient to cause the higher-level event, while an AND gate was used when all defined input events had to occur for the higher-level event to occur (Adamović&Radovanović, 2008). The selection of logical relationships in the developed FTA model was based on the physical meaning of the analyzed mechanisms and their cause-and-effect relationships.

The developed FTA model was used for the qualitative identification and structuring of potential failure pathways. Quantitative estimation of the probability of the top event was not included in this study.

RESULTS AND DISCUSSION

Based on the defined system boundaries and the identified potential failure pathways, a qualitative FTA model of the CO_2-EOR injection system was developed. The developed fault tree is shown in Figure 1, while the event labels and names are provided in Table 1.

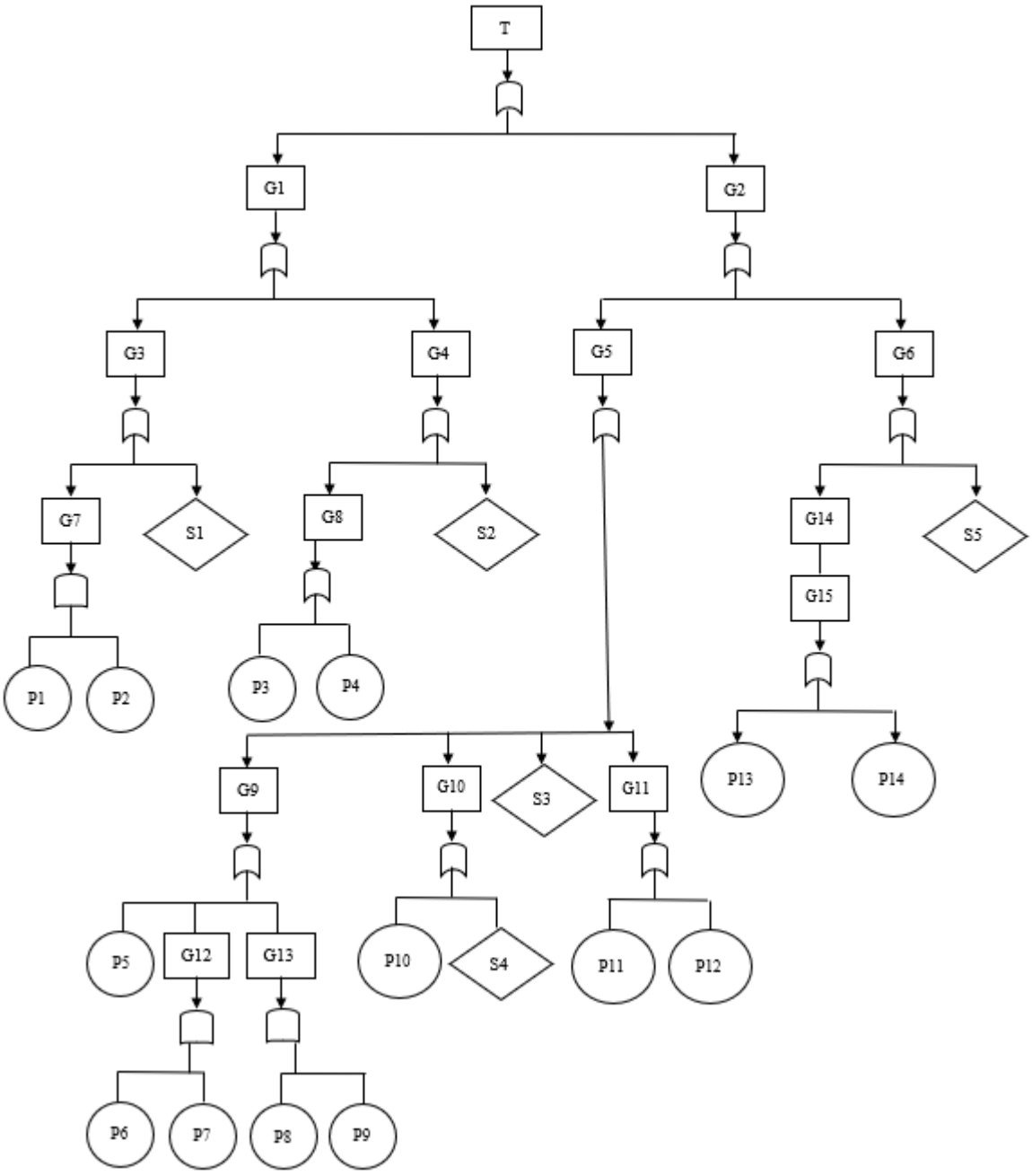


Fig. 1. *Fault tree for the loss of safe and effective CO_2 injection in a CO_2-EOR system*

Table 1. *Event labels and names in the developed FTA model*

Label	Event name
T	Loss of safe and effective CO_2 injection in a CO_2-EOR system
G1	Loss of effective CO_2 injection capability
G2	Loss of safe CO_2 containment during injection
G3	Loss of CO_2 supply / required injection pressure and flow rate
G4	Loss of reservoir injectivity
G5	Loss of injection well integrity
G6	Loss of geomechanical containment due to injection
G7	Corrosion-induced loss of integrity / flow capacity of the surface CO_2 pipeline
G8	Formation damage / near-wellbore plugging
G9	Loss of tubing integrity
G10	Loss of casing integrity
G11	Loss of cement isolation / zonal isolation
G12	Stress-corrosion cracking of tubing
G13	Tubing damage due to freezing at low temperature
G14	Hydraulic fracturing of the containment system due to injection
G15	Excessive reservoir pressure increase
P1	Presence of water / free water phase
P2	Exposure of carbon steel to CO_2-containing fluid
P3	Clay migration / geochemical fluid incompatibility
P4	Precipitate formation due to water–rock reactions / plugging
P5	Progressive CO_2 corrosion of tubing / wall thickness reduction
P6	Corrosive CO_2 environment with an aqueous phase
P7	Mechanical stress / combined loading
P8	Low-temperature CO_2 injection causing cooling below the freezing point
P9	Presence of freezable liquid in the annulus
P10	Casing corrosion progressing to wall penetration
P11	Poor cement placement / initial defects in the cement barrier
P12	Long-term CO_2 degradation of a previously compromised cement barrier
P13	Excessive / inappropriate injection pressure or flow rate
P14	Limited pressure dissipation / unfavorable reservoir pressure response
S1	Loss of compressor capability
S2	Asphaltene deposition impairing injectivity
S3	Loss of packer / annular isolation
S4	Thermomechanical casing failure at low temperature
S5	Activation / opening of existing faults or fractures due to injection-induced changes in pressure and stress state

The top event (T) was defined as the loss of safe and effective CO_2 injection in a CO_2-EOR system and was decomposed into the loss of effective injection capability (G1) and the loss of safe CO_2 containment during injection (G2). This division is based on the functional analysis performed in this study and allows separate consideration of events that affect the designed injection conditions and events that compromise CO_2 containment.

The loss of effective injection capability (G1) includes the loss of CO_2 supply and the required injection pressure and flow rate (G3), as well as the loss of reservoir injectivity (G4). The surface facilities of a typical CO_2-EOR injection system include CO_2 distribution, pipelines to injection wells, additional compression, and measurement and control systems (Novak Mavar et al., 2021), while the reliability of CO_2 infrastructure and supply is recognized as one of the technological limitations of the CO_2-EOR process (Morenov&Shchigolev, 2026). Within G3, corrosion-induced loss of integrity or flow capacity of the surface pipeline (G7) is associated with the presence of a water phase (P1) and exposure of carbon steel to

CO_2-containing fluid (P2), since the presence of water and wetting of the steel surface are key conditions for CO_2 corrosion (Wang et al., 2019). Loss of compressor capability (S1) was retained as an undeveloped event because a detailed analysis of compressor failures was outside the defined scope of this study.

The loss of reservoir injectivity (G4) is associated with formation damage and near-wellbore plugging (G8), as well as asphaltene deposition (S2). Water–rock reactions may contribute to precipitate formation and plugging (Huo et al., 2023), while formation damage and injectivity problems have also been reported from experience with geological CO_2 storage and CO_2-EOR operations (Iyer et al., 2022). Changes in pressure and system composition during contact between CO_2 and crude oil may affect asphaltene stability, and depending on the conditions, CO_2 may increase or decrease the tendency for asphaltene precipitation (Huang et al., 2026). Therefore, asphaltene deposition was treated in the model as a separate but undeveloped pathway leading to loss of injectivity.

The second main branch (G2) includes the loss of injection well integrity (G5) and the loss of geomechanical containment due to injection (G6). Well integrity involves controlled injection while preventing unwanted fluid migration. During CO_2 injection, well barriers are exposed to chemical and mechanical loads, changes in temperature and pressure, and CO_2–brine interactions with well components (Iyer et al., 2022).Therefore, in the developed model, G5 includes loss of tubing integrity (G9), casing integrity (G10), packer/annular isolation (S3), and cement or zonal isolation (G11).

For the tubing, progressive CO_2 corrosion (P5), stress-corrosion cracking (G12), and low-temperature damage (G13) were identified. The combined effect of a corrosive environment and mechanical stress provides the basis for linking a corrosive CO_2 environment with an aqueous phase (P6) and mechanical loading (P7) through an AND gate (Li et al., 2026). A separate, conditional mechanism is the freezing of liquid in the annulus during low-temperature liquid CO_2 injection, where volume expansion and the resulting frost-heave load may lead to tubing and casing failure (Chen et al., 2019). Therefore, this pathway does not represent a universal CO_2-EOR failure mechanism, but rather a scenario that depends on suitable temperature conditions and the presence of liquid that can freeze.

For the casing, corrosion progressing to wall penetration (P10) was identified in addition to low-temperature thermomechanical failure (S4). Studies from the Weyburn CO_2-EOR project reported corrosion damage ranging from small pits to complete casing wall penetration, with possible contributing factors including exposure to injected and formation fluids, CO_2, and conditions in the perforated zone (Laumb et al., 2016). These findings support the relevance of the corrosion pathway in the model but do not justify attributing all observed damage solely to CO_2. Loss of packer/annular isolation (S3) was retained as an undeveloped event, while G11 includes initial defects in the cement barrier (P11) and long-term CO_2 degradation of a previously compromised cement barrier (P12).

The geomechanical branch (G6) includes hydraulic fracturing of the containment system (G14) and the activation or opening of existing faults and fractures (S5). G14 is associated with an excessive increase in reservoir pressure (G15), which may result from inappropriate injection pressure or flow rate (P13) or limited pressure dissipation and an unfavorable reservoir pressure response (P14). Pressure changes during injection are an important factor in geomechanical stability and may be associated with the formation of new fractures or the reactivation of existing fractures and migration pathways (Wang et al., 2020; Shah et al., 2024). However, an increase in pressure does not automatically result in fracturing; geomechanical failure depends on whether the local threshold determined by the properties of the reservoir and containment system is reached.

Overall, the developed FTA shows that the loss of safe and effective CO_2 injection may occur through different but functionally related surface, wellbore, reservoir, and geomechanical pathways. The model enables their systematic identification and cause-and-effect structuring, but it does not rank the events according to risk level because quantitative failure probabilities were not determined.

CONCLUSION

A qualitative FTA model was developed to identify and systematically organize potential pathways that may lead to the loss of safe and effective CO_2 injection in a CO_2-EOR system. By defining the system boundaries and functionally decomposing the top event, two main groups of failures were identified: loss of effective injection capability and loss of safe CO_2 containment during injection.

The developed fault tree shows that the top event may occur through different surface, wellbore, reservoir, and geomechanical pathways. The identified events include problems with CO_2 supply and compression, corrosion, loss of injectivity, loss of well barrier integrity, and pressure changes that may compromise geomechanical containment. The main value of the developed model is that it integrates these different failure mechanisms into a single cause-and-effect structure focused on safe and effective CO_2 injection.

Since the analysis is qualitative, the model does not provide the probability of the top event or rank individual pathways according to risk level. However, the developed FTA structure can provide a basis for further research focused on quantitative assessment and prioritization of the identified failures.

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