Safety Bulletin
Process Safety Considerations for Carbon Capture, Utilization, and Storage (CCUS)

NEBULA
SAFETY & ENVIRONMENTAL

Carbon Capture, Utilization, and Storage (CCUS)

Carbon Capture, Utilization, and Storage (CCUS) is becoming a cornerstone technology in industrial decarbonization strategies. As projects scale, CCUS facilities increasingly resemble high-hazard chemical processing and pipeline operations, requiring robust process safety frameworks comparable to those used in refining, petrochemicals, and industrial gas handling.

While CO_2 is commonly perceived as low risk due to its non-flammable nature, its asphyxiation potential, high-pressure handling requirements, phase behavior, and corrosion mechanisms introduce significant hazards that must be systematically managed.

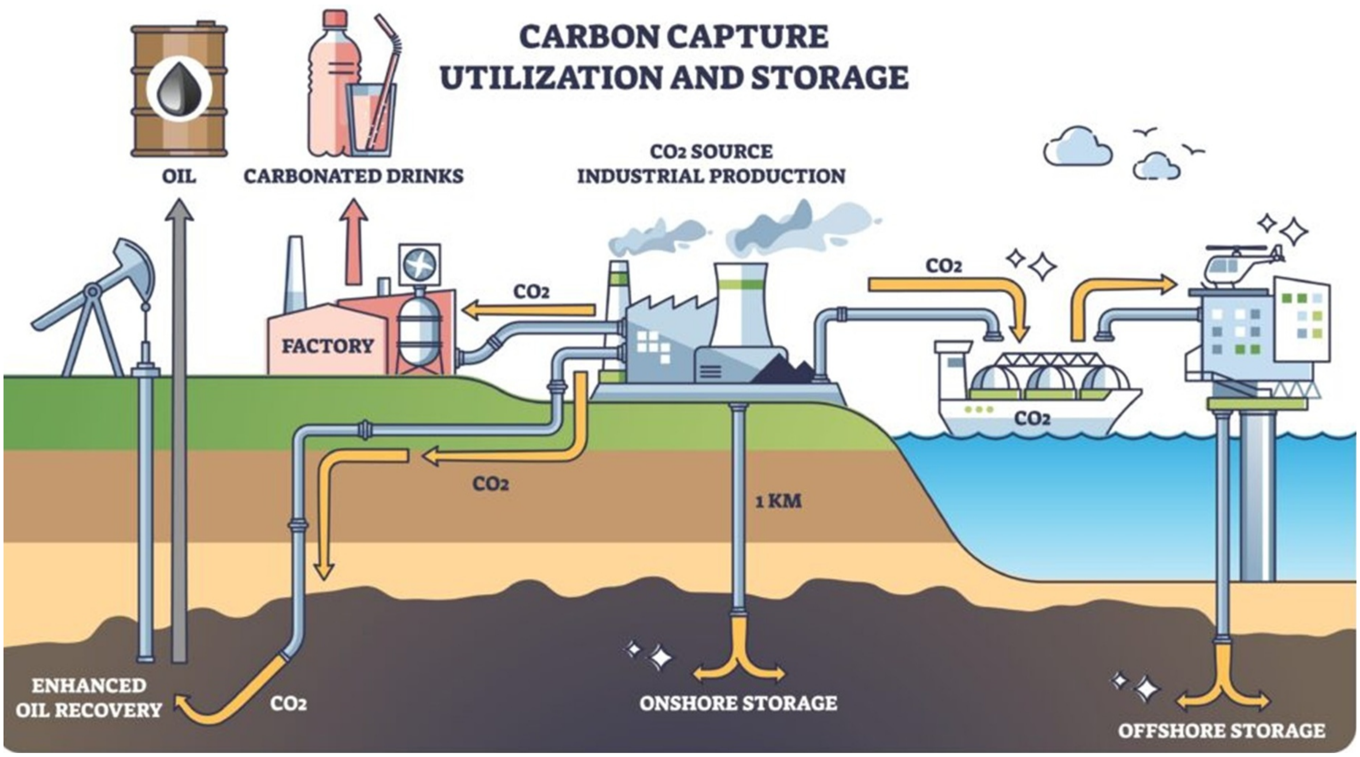

Figure 1: CCUS Process *(source Gexcon.com)*

CO_2 Properties Relevant to Process Safety
Understanding thermophysical and chemical properties is critical for hazard identification:

Dense Gas Behavior
CO_2 vapor is approximately 1.5 times heavier than air, causing it to accumulate in low elevations, trenches, confined spaces, and enclosed process areas.

In This Issue

This Safety Bulletin provides an overview of key process safety considerations for Carbon Capture, Utilization, and Storage (CCUS) systems and emphasizes the importance of applying rigorous hazard identification and risk assessment practices when designing and operating CO_2 handling processes.

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https://www.NebulaSafety.com

Asphyxiation Hazard

CO_2 is colorless and odorless, preventing detection without monitoring instrumentation. Elevated concentrations displace oxygen and pose risks:

- 0.5% (vol): OSHA Permissible Exposure Limit (PEL) and ACGIH Threshold Limit Value (TLV) for 8-hour exposure
- Four percent (vol): Immediately Dangerous to Life or Health (IDLH)
- Eight percent (vol): Dimmed sight, sweating, tremor, unconsciousness, possible death
- Severe exposures (>10% (vol)): Fatal hypoxia within minutes

This makes CO_2 releases comparable to nitrogen or inert gas hazards frequently evaluated in confined space and enclosed process design.

High-Pressure and Phase Transition Hazards

CO_2 transport typically occurs in liquid-phase or supercritical conditions. Rapid depressurization can produce:

- Explosive decompression forces
- Auto-refrigeration and extreme Joule-Thomson cooling
- Solid dry ice particle formation
- Two-phase jet releases and flashing liquid expansion
- Blast overpressure and projectile hazards

These effects complicate consequence modeling relative to conventional hydrocarbon releases.

Figure 2: Pipeline Transfer Rupture Effects *(Source: EENews.net)*

Corrosion and Materials Degradation

Moisture contamination forms carbonic acid, accelerating corrosion in carbon steel systems. Impurities such as SO_x, NO_x, O_2, and H_2S further increase:

- Pitting corrosion
- Stress corrosion cracking
- Embrittlement risks
- Pipeline wall thinning

Materials compatibility assessments and dehydration specifications are therefore safety-critical design elements.

Stage-Specific CCUS Hazards

Capture Facilities
Capture systems involve chemical absorption, adsorption, membranes, or cryogenic separation processes operating at elevated temperatures and pressures. Hazards include:

- Solvent degradation and toxic byproducts
- Amine system corrosion and fouling
- Thermal runaway reactions
- Large rotating equipment failures
- Impurity exposure risks (CO, SO_2, NO_2)

These systems pose large hazards and warrant Process Hazard Analyses.

Compression and Transportation
Dense-phase CO_2 pipelines present unique risks compared to natural gas transmission:

- Dispersion of heavy gas clouds
- Soil ejection and crater formation following rupture
- Corrosion from operations

Pipeline routing must consider population density, topography, and meteorological dispersion conditions.

Geologic Storage and Injection
Subsurface sequestration introduces geotechnical and containment risks:

- Rock layer integrity failure
- Environmental Impact
- Groundwater acidification from dissolved CO_2 migration

Wellbore integrity and long-term monitoring systems are critical safeguards.

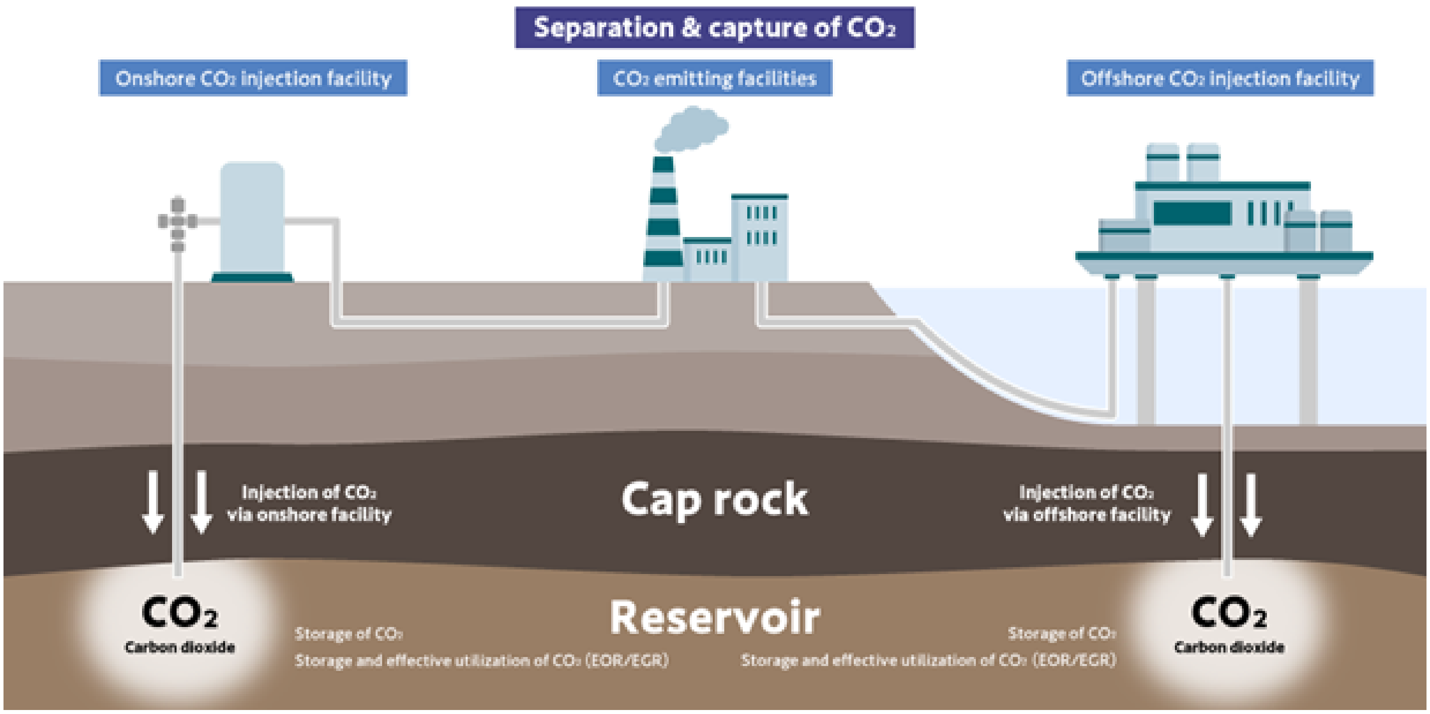

Figure 3: CO_2 Reservoirs *(Source: Inpex.com)*

Historical CO_2 Release Incidents

Several major incidents demonstrate the real-world consequences of large-scale CO_2 releases:

• Satartia (2020): A pipeline rupture released a dense CO_2 cloud that displaced oxygen, created a 40-foot crater, stalled internal combustion engines, and hospitalized dozens of residents.

• Sulphur (2024): A high-pressure pipeline leak triggered community shelter-in-place orders due to atmospheric oxygen displacement risks.

These events highlight that CO_2 behaves as a mass-asphyxiant hazard capable of producing community-scale consequences, similar to toxic industrial chemicals.

Implications for Process Hazard Analysis (PHA)

CCUS facilities should be evaluated using rigorous hazard identification methodologies:

Applicable Studies

- HAZID for early project risk screening
- HAZOP for process deviations
- LOPA for safeguard adequacy
- QRA for offsite consequence modeling
- Facility siting studies for vapor cloud exposure
- Dispersion modeling for dense gas releases

Key Hazard Scenarios

- Catastrophic pipeline rupture
- Vessel overpressure and BLEVE-like events
- Compressor seal failures
- Accidental confined space releases
- Storage site leakage migration
- Fire suppression system misactivation

Recommended Risk Management Measures

CCUS risk management systems can incorporate:

✔ Oxygen and CO_2 fixed gas detection systems
✔ Dense gas dispersion and consequence modeling
✔ Pipeline integrity management
✔ Ventilation design for low-lying areas
✔ Integrated emergency response planning with local authorities
✔ Workforce training on oxygen-deficiency recognition

Key Takeaway

Although positioned as an environmental solution, CCUS introduces complex major accident hazards that require mature process safety management systems. Treating CCUS facilities as low-hazard infrastructure can lead to underestimating risks associated with high-pressure CO_2 systems, dense gas dispersion, and large-scale releases.

Integrating process safety from early design stages is essential to ensure decarbonization efforts do not introduce unintended risks to workers, the public, or the environment.

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