

Guideline for Materials Selection and Corrosion Control for CO₂ Transport and Injection

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Foreword

The purpose of this document is to provide guidance on materials selection and corrosion control for engineers in the design and identification of operating limits for projects that involve CO₂ transport and injection. It should be used as a guide to help identify specific requirements which can be tailored for each project rather than as definitive requirements used straight from the document. References are also made to other relevant documents and standards. The guidance provided for an initial design should help the engineer focus on the most critical issues related to CO₂ transport and injection. It is a rapidly growing subject area and much exploratory technical work is still being executed, and as such this document should be seen as a starting point with future updates and new insights to be expected.

Scope

The scope of this document is to provide guidance to select materials and ensure long time integrity via effective corrosion control for CO₂ transport and injection, including identification of a safe CO₂ specification.

Rationale

Carbon Capture and Storage (CCS) is a vast growing industry posing challenges to materials and process integrity that are different from more conventional industries. This document aims to provide guidance based on the state of the art to help identify a robust design, to avoid critical items being overlooked, and to avoid and control early degradation and failures.

Referenced Standards and Other Consensus Documents

The latest edition, revision, or amendment of the referenced documents in effect shall govern unless otherwise dated.

AMPP, www.ampp.org:

ANSI/NACE MR0175/ISO 15156	Petroleum and Natural Gas Industries — Materials for Use in H ₂ S-containing Environments in Oil and Gas Production
NACE TM0316	Standard Test Method Four-Point Bend Testing of Materials for Oil and Gas Applications
NACE TM0177	Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H ₂ S Environments

American Society of Mechanical Engineers (ASME), www.asme.org:

ASME IX	Welding Qualifications
ASME B31.3	Process Piping, Code for Pressure Piping
ASME B16.5	Pipe Flanges and Flanged Fittings
ASME VIII div I	Boiler and Pressure Vessel Code ASME VIII div 1 (Rules for Construction of Pressure Vessels)

ASTM International, www.astm.org:

ASTM E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials
ASTM A203	Standard Specification for Pressure Vessel Plates, Alloy Steel, Nickel
ASTM D1329-16	Standard Test Method for Evaluating Rubber Property - Retraction at Lower Temperatures (TR Test)
ASTM D2137-11	Standard Test Methods for Rubber Property—Brittleness Point of Flexible Polymers and Coated Fabrics

American Petroleum Institute (API), www.api.org:

API 579 / ESMEFFS-1	Fitness for Service Part 3-Assessment of Existing Equipment for Brittle Fracture
API RP 582	Welding Guidelines for the Chemical, Oil, and Gas Industries
API RP 584	Integrity Operating Windows (IOWs)
API 14E	Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems
API 617	Axial and Centrifugal Compressors and Expander-compressors
API 5L	Line Pipe
API TR5C3	Calculating Performance Properties of Pipe Used as Casing or Tubing
API 5CT	Specification for Casing and Tubing
API 5CRA	Specification for Corrosion Resistant Alloy Seamless Tubes for Use as Casing, Tubing and Coupling Stock
API 6ACRA	Age-hardened Nickel-based Alloys for Oil and Gas Drilling and Production Equipment

CSA Group, www.csagroup.org:

CSA Z245 20 Series	Plant Applied external coatings for steel pipe
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Det Norske Veritas (DNV), www.dnv.com:

DNV RP-F104	Design and operation of carbon dioxide pipelines
DNV RP-B401	Cathodic Protection Design
DNV ST-F101	Submarine Pipeline Systems
DNV ST-F109	On-bottom stability design of submarine pipelines

European Federation of Corrosion (EFC), www.efcweb.org:

EFC 46	Corrosion in Amine Treating Units
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European Standards, www.en-standard.eu:

EN 13445	Unfired Pressure Vessels
EN 13480	Metallic Industrial Piping

International Association of Oil & Gas Producers (IOGP), www.iogp.org:

IOGP S-614	Supplementary Specification to API Standard 660 Shell-and-Tube Heat Exchangers
IOGP S-616	Supplementary Specification to API Specification 5L and ISO 3183 Line Pipe
IOGP S-619	Specification for Unfired, Fusion Welded Pressure Vessels
IOGP S-705	Supplementary Specification to API Recommended Practice 582 for Welding of Pressure Containing Equipment and Piping
IOGP S-715	Supplementary Specification to NORSOK M-501 Coating and Painting for Offshore, Marine Coastal and Subsea Environments
IOGP Report 544	Standardization of barrier definitions, Supplement to report 415

International Electrotechnical Commission (IEC), www.iec.ch:

IEC 60812	Failure modes and effects analysis (FMEA and FMECA)
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International Organization for Standardization (ISO), www.iso.org:

ISO 17349	Petroleum and natural gas industries — Offshore platforms handling streams with high content of CO ₂ at high pressures
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ISO 27913	Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems
ISO 15614	Specification and qualification of welding procedures for metallic materials — Welding procedure test
ISO 17782	Petroleum, petrochemical and natural gas industries — Scheme for conformity assessment of manufacturers of special materials
ISO 10400	Petroleum and natural gas industries — Formulae and calculation for casing, tubing, drill pipe and line pipe properties
ISO 11960	Petroleum and natural gas industries — Steel pipes for use as casing or tubing for wells
ISO 13680	Petroleum and natural gas industries — Corrosion-resistant alloy seamless tubes for use as casing, tubing and coupling stock technical delivery conditions
ISO 21809	Petroleum and natural gas industries — External coatings for buried or submerged pipelines used in pipeline transportation systems
ISO 15589	Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline transportation systems
ISO 12944	Paints and varnishes — Corrosion protection of steel structures by protective paint systems
ISO 2063	Thermal spraying — Zinc, aluminium and their alloys
ISO 23936	Petroleum, petrochemical and natural gas industries — Non-metallic materials in contact with media related to oil and gas production
ISO/TR 27921	Carbon dioxide capture, transportation, and geological storage — Cross cutting issues — CO ₂ stream composition
ISO 9001	Management Systems
ISO 148-1	Metallic materials - Charpy pendulum impact test — Part 1: Test method

Standards Norway, www.standard.no:

NORSOK M 506	CO ₂ Corrosion Rate Calculation Model
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European Union, www.eur-lex.europa.eu:

EU Directive 2014/68/EU	Pressure Equipment Directive
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Materials Definitions

This document provides guidance to material selection based on generic type materials and aims not to be too specific and not to exclude any suitable material. Therefore, materials are not identified by a specific grade, but as a generic group of materials. The document uses the following materials and abbreviations:

- CS refers to a ferritic carbon steel available in many grades (e.g., API 5L – X-65)
- LT-CS refers to a ferritic carbon steel available with a specific low-temperature toughness
- LAS refers to low alloyed steel
- Ni-Steel (e.g., 3.5 Ni) indicates a steel grade that contains x% nickel that raises the low-temperature toughness of the steel conforming to ASTM 203 grade E
- 13 Cr steel refers to martensitic steel that contains at least 13% chromium, (e.g., UNS S41000)
- 16 Cr refers to a martensitic steel that contains at least 16% chromium, (e.g., UNS S43000)
- ASS 316L refers to an austenitic stainless steel with a PREN (Pitting Resistance Equivalent Number) > 25 (e.g., UNS S31603)
- DSS 22 Cr refers to a duplex stainless steel with at least 22 % chromium content and typically a PREN > 30 (e.g., UNS S31803)
- SDSS 25 Cr refers to a super duplex stainless steel with at least 25 % chromium content and typically a PREN > 40) e.g., (UNS S32760)

- SASS 6 Mo stainless steel refers to a super austenitic stainless steel that contains at least 6% molybdenum with a PREN > 40 (e.g., UNS S31254)
- Alloy 625 (UNS N06625) refers to a high-quality nickel alloy grade
- Material grades used for wells are defined in reference to API 5CT and API 5CRA
- CA refers to Corrosion Allowance
- PREN is used as an indication of the corrosion resistance. As an alternative, the PRE_w may also be used, where:
 $PREN = \%Cr + 3.3 \%Mo + 16\%N$
 $PRE_w = \%Cr + 3.3 (\%Mo + 0.5 \times \%W) + 16\%N$

Introduction

The aim of this document is to describe an approach to materials selection and corrosion control that can address the specific requirements of a Carbon Capture and Storage (CCS) project. In addition to corrosion, other degradation mechanisms like cracking that are controlled via materials selection are covered.

This content is largely based on the accumulated knowledge and expertise that has been published.^{1,2} Besides the guidance in this document, specific topics requiring more detail can be found in the references. The main focus of this document is on compression, transport, and injection of CO₂. Processing and cleaning of CO₂ are not addressed in detail.

The document provides a structured work process for materials selection and corrosion management for CCS. Other approaches may exist. The one described in this document is considered to be a good practice. The CCS process with its specific challenges for materials selection is outlined in the first section. The remaining part of the document provides background on failure mechanisms that can be used as input to a Failure Mode and Effect Analysis. Key critical success factors for a CCS project have been identified as:

1. Definition of the operating envelope, including potential upsets that may trigger drop out of water, corrosive liquids, and/or a drop in temperature.
2. Setting and maintaining safe impurity limits in the CO₂ to limit potential corrosion damage.
3. Materials selection based on:
 - a. Carbon steel (CS) being a base case and controls being implemented to ensure its safe use for the desired service life.
 - b. Resistance to H₂S and other cracking mechanisms, sufficient low-temperature toughness, and the ability to arrest running fracture, in accordance with the avoidance of sudden failure mechanisms as defined in the materials selection philosophy.
 - c. Operation that allows material degradation to occur in a controllable and timely detectable way (to allow for adjustment/control).

Background

A substantial amount of the world's rising energy demand is forecast to still be met by fossil fuels over the next decade. Carbon Capture and Storage (CCS) is a key available technology to mitigate emissions from large-scale fossil fuel use. Therefore, developing and commercializing this technology is essential to help reduce the impact on climate change during the transition to low-carbon alternatives. CCS primarily involves capturing the CO₂ arising from energy-related and industrial sources, treating of the CO₂ to remove impurities, and then compressing, transporting, and injecting it in a storage site (see [Figure 1](#)) to ensure long-term isolation from the atmosphere.

In using fossil fuels to generate power, the purity of CO₂ emissions is not an important parameter and as a result, the quality of CO₂ for CCS transport and injection will be predominantly dictated by the CO₂ capture technology employed at the plant with secondary consideration of the pipeline and storage limitations.

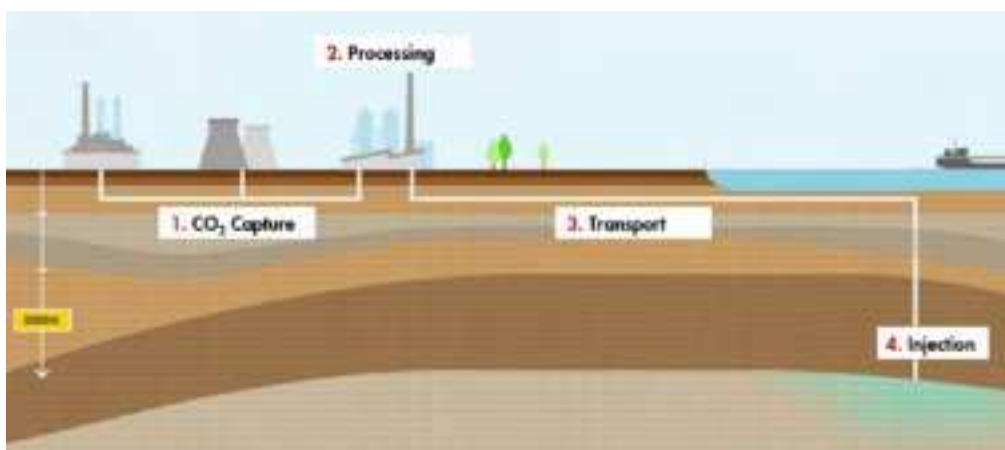


Figure 1: Diagram Showing an Example of the CCS Process^{1,2}

CO₂ source

Removing impurities down to very low concentrations may create a significant energy requirement and commercial impact. Consequently, CO₂ captured from power generation and industrial sources for CCS is likely to contain many impurities. For CCS projects, threats related to the purity of the CO₂ can be classified by the gas source as:

- Relatively clean CO₂ gas. There is a lot of experience with CO₂ gas injection used for EOR (Enhanced Oil Recovery) and re-injection of CO₂ from oil and gas production. This is a relatively clean CO₂ source and experience has shown that there are few operational problems, provided the fluid is kept relatively pure and the water content is controlled.^{3,4}
- Impure CO₂ gas. For CCS, the CO₂ can originate from combustion or from a range of industrial sources (often termed Anthropogenic). The impurities include those present in the gas source (e.g., H₂O, NO_x, SO_x, O₂), as well as those present from the cleaning process (e.g., glycol, amines), or other project-specific impurities (e.g., NH₃, methanol, glycol, etc.). Impurities can have a significant impact on the corrosivity of the CO₂.

Recently proposed CCS projects aim to collect, pressurize, transport, and inject CO₂ from multiple industrial sources. These projects do not include cleaning, and there is a need to identify, monitor and control the impurity limits in the CO₂ specification from the individual emitters.

CCS Process

Degradation mechanisms mentioned in this section will be given more attention in a later section ("Input for a Failure Mode and Effect Analysis")

Processing

To capture CO₂, a range of processes are available that have benefits and drawbacks and can usually be optimized specifically for a project. These processes largely involve amine-type solvent treatment, often in combination with glycol treatment. The materials selection for CO₂ processing equipment should be based on an IOW (Integrity Operating Window) approach to define the operational limits for a given material.

The regeneration of contaminated solvents may require elevated temperatures. These can cause degradation of the solvent to form organic acids, and sometimes reducing environments that can be corrosive to some corrosion-resistant alloys. The material of choice is invariably CS, but if this is not suitable, then material upgrades typically include AISI 316, 22Cr duplex, or 6 Mo stainless steels. There is significant experience with materials used in amine treatment units, and guidance can be found via EFC 46.

The materials selection will depend on the specific process and requires a detailed evaluation of the options, possibly including some qualification testing. The approach of identification of corrosion loops with materials selected against controlled IOWs is familiar within the industry and will not be covered in detail here.

Transport

Materials selection of transport pipelines (or vessels for transport or temporary storage) typically involves understanding the phase behavior of the CO₂. The gas for transport is typically compressed to a pressure where the CO₂ becomes a liquid / dense phase (refer to [Figure 3](#)), and this creates some specific challenges which are covered below. Since transport pipelines can be many kilometers in length, the ability to use CS is often a primary factor in the overall project economics. Understanding the phase behavior and the impact of the CO₂ composition including its impurities has proven to be essential in identifying the potential threats of corrosion and other forms of degradation.

For transport via pipelines, ISO 27913 and DNV RP-F104 have been developed to provide some initial guidance, and ISO 17349 covers offshore handling of CO₂ streams at high pressure. Transport of CO₂ using non-metallic materials creates other challenges (e.g., high pressure vs. diameter, low-temperature impact) and this is currently an area of opportunity for further development.

For several projects, the ship transport of CO₂ has been suggested and it is worth mentioning that the threats outlined in the section on corrosion can also be expected with this transport mode.^{5,6} The impurity limits for ship transport may be even more critical with respect to liquid drop-out and accumulation.⁶ Corrosion under such conditions remains an area of ongoing research.

A possible additional issue with ship transport is the required cryo-compressed conditions that can create temperatures significantly below -30 °C. These temperatures are below the T_g (glass transition temperature) of a wide range of polymeric materials and their selection requires detailed analysis.⁷

Injection

Injection of CO₂ via a well into an underground storage creates specific challenges that are somewhat different from typical oil and gas production wells. The flow is in the opposite direction, and the CO₂ stream typically includes oxygen as an impurity. Temperatures can be much lower, especially for upset conditions where a drop in pressure causes Joule-Thompson cooling. The low-temperature exposure requires low-temperature toughness and creates additional requirements for selected materials.

The oxygen present in CO₂ requires consideration when a reservoir is selected that contains a high saline aquifer that can come in contact with the materials used at the bottom of the well (e.g., lower completion tubing and liner). The presence of O₂ with saline water at an elevated (downhole) temperature may require highly resistant alloys that often need specific qualification unless a suitable well design is used (e.g., installing a barrier valve downhole to prevent flowback). Other impurities from the captured CO₂, such as SO_x, NO_x, H₂S, etc. are also introduced into the injection well. Their potential effects should also not be ignored and require assessment once the full composition range of the CO₂ is known. Control of O₂ ingress and O₂ contamination is important in oil and gas production systems.

Another topic relating to injection of CO₂ into a storage reservoir is the potential presence of solids that can plug a well; this may require the use of filters. Compared to oil and gas production, fewer solids with smaller particle sizes can be expected. In combination with the relatively lower velocities in dense phase CO₂, erosion is not expected to be a significant issue.

Equipment

In addition to the main materials of construction for each section of the CCS process, there are components like valves, pumps, seals, connectors, and other specific equipment, which require due consideration in the overall materials selection. Operating with a CO₂ specification that can cause acid formation may pose a specific threat for vessels and separators where flow is relatively stagnant, which may trigger precipitation of these acids. Some designs may pose a specific risk of galvanic couples between different metal grades (causing galvanic corrosion), and the presence of crevices between pipe connections can introduce crevice corrosion. Moreover, the selection of non-metallic materials (especially elastomeric seals) introduces specific challenges, and these will be covered later in this document.