

Guidance for Materials Selection and Corrosion Control in CO₂ Transport and Injection for Carbon Capture and Storage

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ABSTRACT

Carbon Capture and Storage (CCS) is a key technology to mitigate emissions from large-scale fossil fuel use. CCS primarily involves capturing the CO₂ arising from energy-related and industrial sources, treating of the CO₂ to remove impurities, and injecting it in a storage site to ensure long-term isolation from the atmosphere. The specific difference in relation to experience with relatively pure CO₂ injection is caused by the impurity of the CCS CO₂ which will be dictated by the CO₂ source and capture technology employed.

The aim of this work is to identify an approach to materials selection and corrosion control that can address the specific requirements of a CCS project. Depending on the phase envelope and CO₂ composition, separate liquid phases may be formed. It has been identified that these phases can comprise of water (causing CO₂ corrosion) or reaction products including strong acids and elemental sulphur.

The type of liquids formed and shifts in the phase envelope can significantly influence materials integrity due to corrosion, and impact on the toughness and degradation of polymers.

In this paper guidance is provided with a process to select materials and ensure corrosion control. It is recommended to start each project with the identification of the CO₂ specification and operating scenarios, including upsets that might occur during the service life. Input is provided that can be used for a Failure Mode and Effect Analysis (FMEA) specific to CO₂ transport and injection.

Key words: CO₂ corrosion, Carbon Capture and Storage Materials Selection, Impurities, CO₂ transport, dense phase CO₂

INTRODUCTION

The aim of this work is to identify an approach to materials selection and corrosion control that can address the specific requirements of a Carbon Capture and Storage (CCS) project. This work is largely based on the accumulated knowledge and expertise that has been published ^[1,2]. Besides the direct guidance from this document, specific topics may require more detail that can be found in the references.

The paper provides a structured work process for materials selection and corrosion management. The CCS process with its specific challenges for materials selection is outlined in the first section. The remaining part of the paper provides a background on failure mechanisms that can be used as input to the Failure Mode and Effect Analysis,

Key critical success factors for a CCS project have been Identified as:

1. Identification of the operating envelope including potential upsets that may trigger drop out of water, corrosive liquids or a drop in temperature.
2. Setting and maintaining safe impurity limits in the CO₂
3. Materials selection based on:
 - a. Resistance to H₂S related cracking, sufficient low temperature toughness, and the ability to arrest running fracture, in accordance with the avoidance of rapid failure mechanisms as defined in the materials selection philosophy.
 - b. Operation that allows material degradation to occur in a controllable and detectable way.

BACKGROUND TO THE CCS PROCESS

A substantial amount of the world's rising energy demand is forecast to still be met by fossil fuels over the next decade ^[3]. Carbon Capture and Storage (CCS) is a key available technology to mitigate emissions from large-scale fossil fuel use. Therefore, developing and commercialising this technology is essential to help reduce the impact on climate change ^[4,5]. 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 to ensure long-term isolation from the atmosphere ^[6,7].

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.

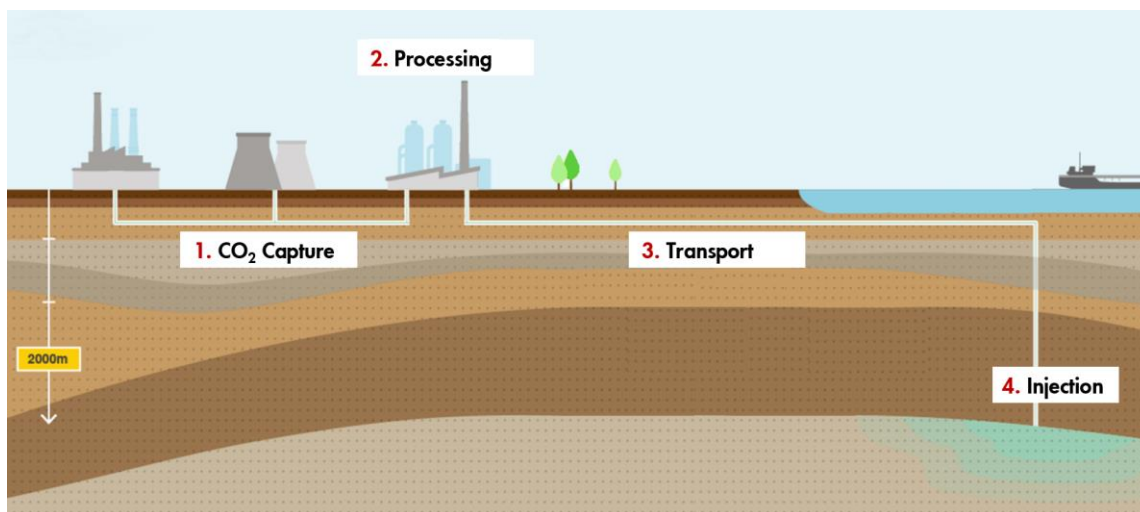


Figure 1: Diagram showing an example of the CCS process: Modified from Shell.com [8].

CO₂ source

Removing impurities down to very low concentrations may create a significant energy requirement and cost penalty ^[4]. 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). 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 ^[4,9,10,11].
- Impure CO₂ gas. For CCS the source of CO₂ can originate from combustion or from a range of industrial sources. 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, pressurise, transport and inject CO₂ from multiple industrial sources. These projects do not include cleaning and have to identify, monitor and control the impurity limits in the CO₂ specification to the individual emitters.

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 which 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 carbon steel but if this is not suitable then materials upgrade typically include AISI 316, 22Cr duplex or 6Mo stainless steels. The materials selection will depend on the specific process and requires a detailed evaluation of the options, possibly including some qualification testing. This approach is familiar within the industry and will not be covered in detail here.

Transport

Materials selection of transport pipelines (or vessel transport) typically involves understanding of the behaviour of the CO₂. The gas for transport is normally compressed to a pressure where the CO₂ becomes a liquid / dense phase (refer Figure 2), and this creates some specific challenges which are covered below. Since transport pipelines can be many kilometres in length the ability to use carbon steel can be a make or break for a project. Understanding the phase behaviour and the impact of the CO₂ composition including its impurities has proven to be essential in identifying the potential threats of corrosion or other forms of degradation.

For transport via pipelines ISO Standard 27913^[12] has been developed to provide some initial guidance, as well as ISO 17349^[13] for offshore handling of CO₂ streams at high pressure.

For several projects 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 ship transport ^[14]. A possible additional issue with ship transport is the required cryo-compressed conditions that can create temperatures down to -30°C. These temperatures are below the T_g (glass transition temperature) of a wide range of polymeric materials and selection requires detailed attention ^[15].

Injection

Injection of CO₂ via a well into an underground storage provides specific challenges that are somewhat different to 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. Presence of O₂, with saline water at an elevated (downhole) temperature may require highly resistant alloys with specific qualification, unless a suitable well design solution 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, and other are also introduced into the injection well. Their potential effects should also not be ignored and require attention.

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 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 paper.

PROPOSED WORK PROCESS

This work identifies an approach for materials selection and corrosion control that can address the specific requirements of a CCS project. A work process is proposed as presented in Figure 2 and described below.

- A. The project should start with providing a design basis, including:
 1. The projects CO₂ specification (composition), with the upper limits of the potential impurities,
 2. The operating envelope as a range of pressure and temperatures,
 3. A review of transients and upsets for each part of the CCS process.
- B. Based on these data a Failure Mode and Effect Analysis (FMEA)^[16] should be done that includes:
 1. A review of potential catastrophic failures; details on specific mechanisms relevant to CCS that require attention,
 2. A corrosion analysis: this should include the potential upset and transient conditions,
 3. Failure mechanisms applicable to corrosion resistant alloys (CRAs) or non-metallics and polymers.
- C. A risk analysis should be done to ensure the safety and feasibility of the project. The solution should be based on a balance between the operating envelope, CO₂ specification and selected materials.
- D. Based on this risk analysis a materials selection can be done that includes the selected materials, their identified Integrity Operating Window (IOW)^[17] as well as the defined design and operating limits. In addition to the selected materials, control options (barriers)^[18] and their effective limits should be identified and effectively implemented.
- E. During the Operate phase of the project the following items should be monitored on a regular basis and controlled within the defined limits:

1. The operating envelope including pressure, temperatures and upsets/transients which require special attention,
 2. CO₂ composition of critical components identified in the CO₂ specification,
 3. Corrosion management aspects including inspection and corrosion monitoring.
- F. If everything is within the defined limits, operation can continue, but if the limits are exceeded a Management Of Change (MOC)^[19] review should be executed.

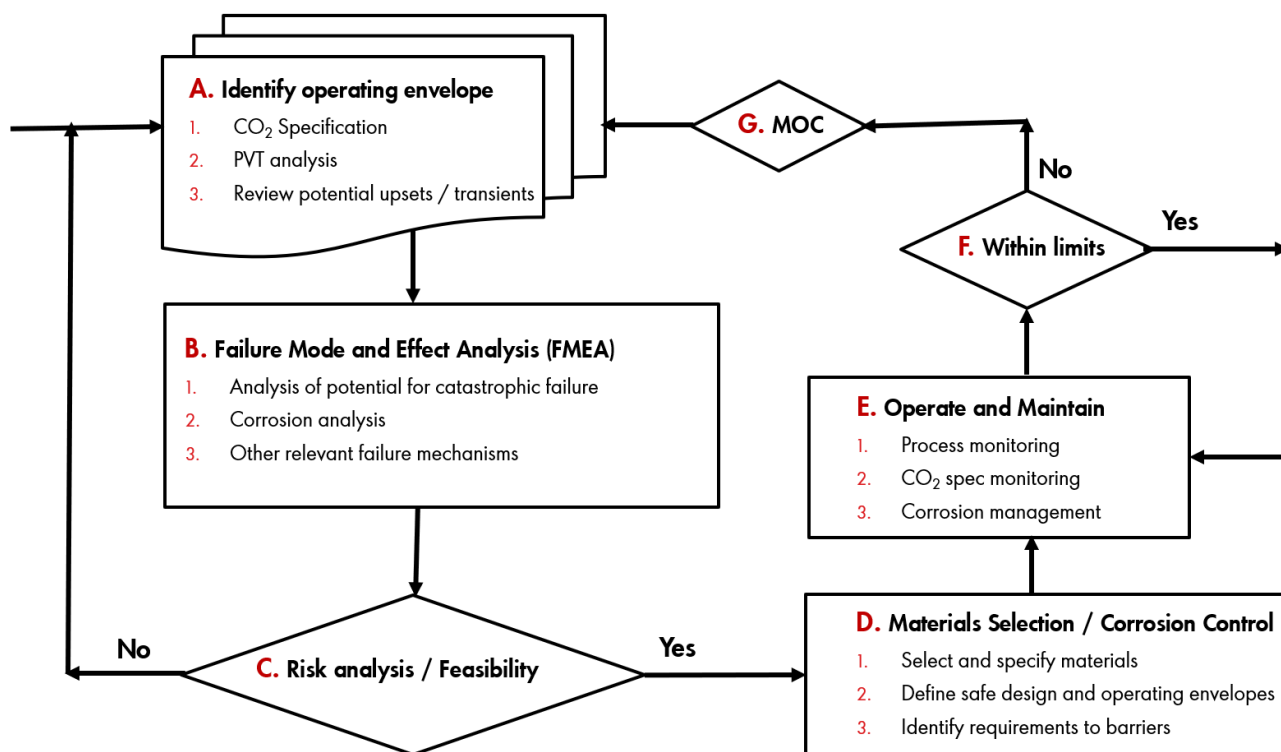


Figure 2: Materials Selection Process (note: steps A. B. C. resulting in D. require review during each project phase).

Steps A, B, and C resulting in step D in which materials are selected and the IOWs are defined should be implemented at each phase in the project. This will ensure that the required safe limits are set, and any changes are properly addressed.

It can be expected that testing and modelling is required to achieve an optimal design and therefore sufficient time should be scheduled in the overall project process. Apart from materials qualification special attention should be given to identifying phase behaviour and the impact of impurities (as identified in the CO₂ specification).

Steps E, F and G cover the operate phase where asset integrity monitoring should include:

- operations within the defined limits of the operating envelope,
- the components of the CO₂ specification
- corrosion management including inspection, and corrosion monitoring.

If operation does not stay within the defined limits, or if unexpected degradation is found, a MOC review may be required that should include a revisit of steps A, B and C.

MATERIALS SELECTION OPERATING ENVELOPE AND CO₂ SPECIFICATION

Materials Selection Philosophy

In developing a generic materials selection and corrosion control strategy the following two options exist:

1. Threats that can be controlled (using barriers) and/or detected within a timely manner and can be tolerated with the application of a proper control strategy.
2. Threats that can lead to rapid failure that cannot be controlled or (timely) detected and require selection of resistant materials.

Degradation mechanisms that can be controlled typically include corrosion and, in this case particularly CO₂ corrosion.

In this section the threats that can potentially lead to catastrophic failure and require to be designed out via selection of resistant materials are briefly reviewed.

Materials selection

For the materials selection of any unit it is important that the defined limits for the materials are kept and that the unit is operated within the IOW for the unit. Materials are typically resistant for a specific IOW, (the relevant IOW should cover all operating conditions including upsets). IOW identification should include operating conditions (e.g. P, T and flow) as well as the detailed composition of the CO₂ specification.

Critical factors for material selection for a CCS project (to avoid rapid degradation) include resistance to H₂S cracking, sufficient low temperature toughness and the ability to arrest running fracture.

One of the aspects in a CCS project that might have an impact different from a typical oil and gas production project is the potential for low temperature exposure and what this may do to adhesion and durability of the coating.

Selection of CRA materials for CO₂ streams needs validation of the de-passivation limits (pH, [O₂], [Cl⁻] and temperature), and the evaluation of the potential for condensation. For materials in wells the potential of flow back of brine needs to be assessed.

For polymer materials that are in contact with CO₂, a qualification/validation program is recommended that includes rapid gas decompression and the potential impact of impurities.

Operating Envelope

In a CCS project the potential for degradation and corrosion can be derived from the conditions in the CO₂ stream. These conditions are a combination / interaction between phase behaviour and composition (CO₂ specification).

Figure 3 (next page) shows the phase diagram for CO₂ with only one impurity (H₂O) and one concentration. As can be seen from this figure a liquid (water) phase may be present depending on pressure and temperature. The liquid phase (in this case water) can cause corrosion or trigger another failure mechanism. The phase diagram applicable to the project will however be much more complicated. Actual phase behaviour strongly depends on the composition (i.e. impurity concentration) of the CO₂ and the liquids formed, these can include water as well as water mixtures (e.g. with alcohol) and even reaction products.

To be able to understand the risk of liquid drop out one needs to understand the full operating envelope. Since transients and upset conditions may trigger a phase transition that causes liquid drop out with longer term consequences, these operating conditions require evaluation to understand the potential failure modes. Some specific parts of the design (seals, valves, separators, etc.) require extra attention with respect to the evaluation of the potential for accumulation of corrosive liquids. For a robust analysis of the process phase behaviour considering the full operating envelope it is recommended to involve expert support.