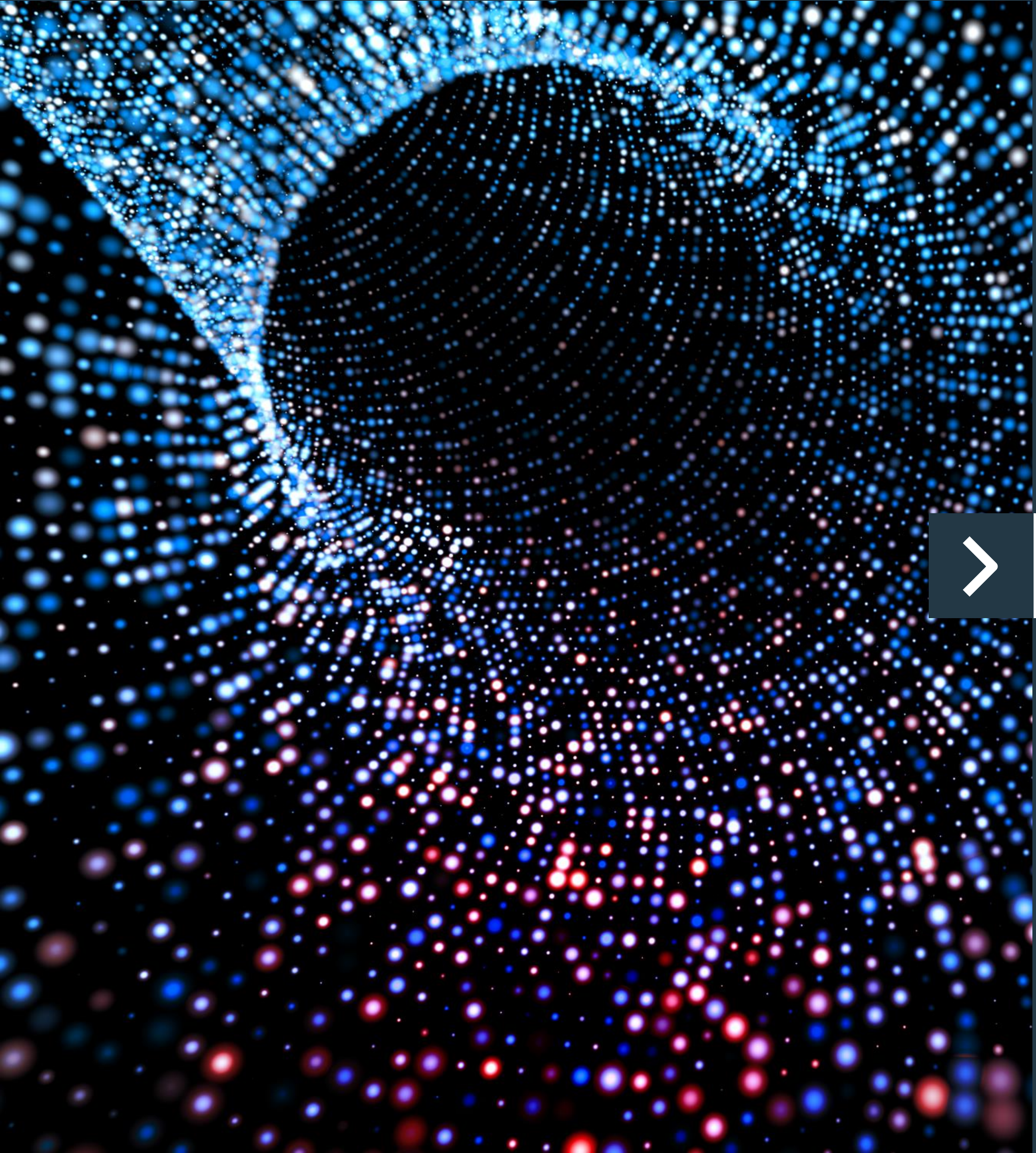

Joint Industry Project

# Industry Guidelines for Setting the CO2 Specification in CCUS Chains

## An Introduction to Impurities

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# Agenda

1. Overview  - Objectives of the Joint Industry Project (JIP)
2. Impact of Impurities
3. JIP Work Packages
4. Summary
5. Q&A

# JIP Notices

## Disclaimer

- The guidelines have been approved by the JIP Steering Committee and are intended to provide general information on the topic. The Steering Committee makes no representations or warranties of any kind, express or implied, regarding the accuracy, completeness, or suitability of the information contained herein. Users of these guidelines assume all risks associated with their application. The Steering Committee accepts no liability for any reliance placed on these guidelines or for any consequences arising from their use.

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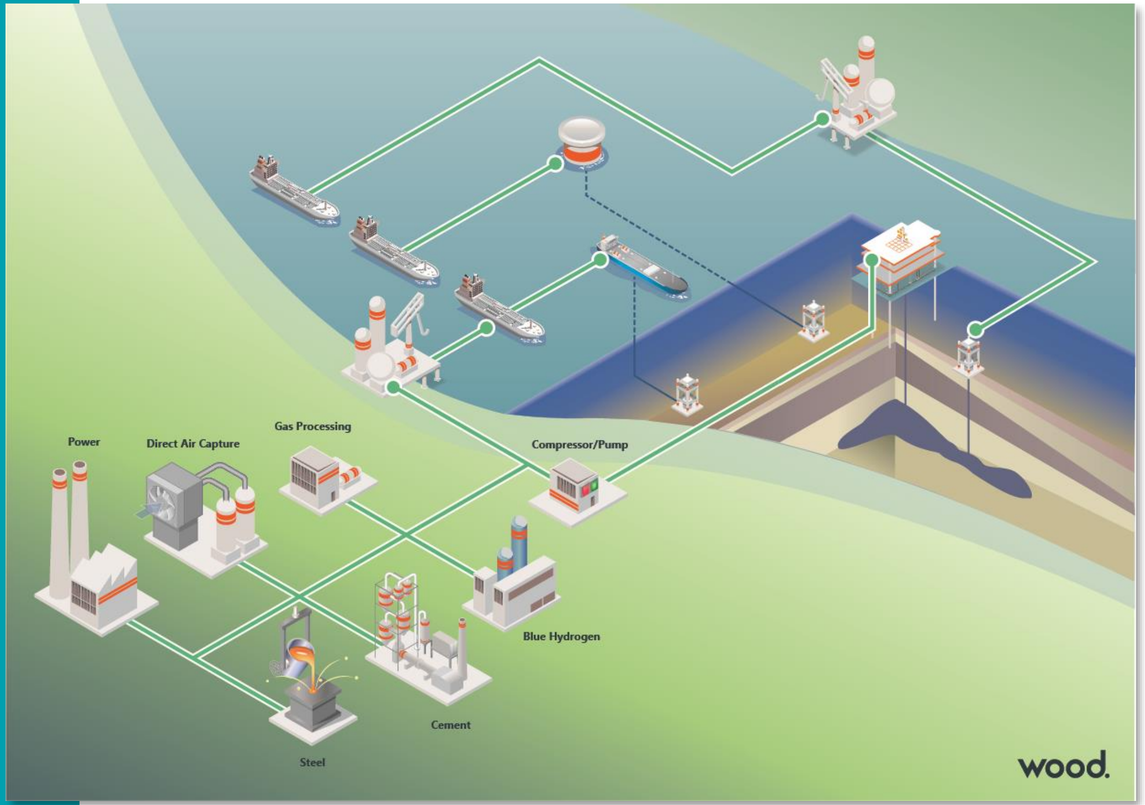
# CO2 Specification in CCUS Chains

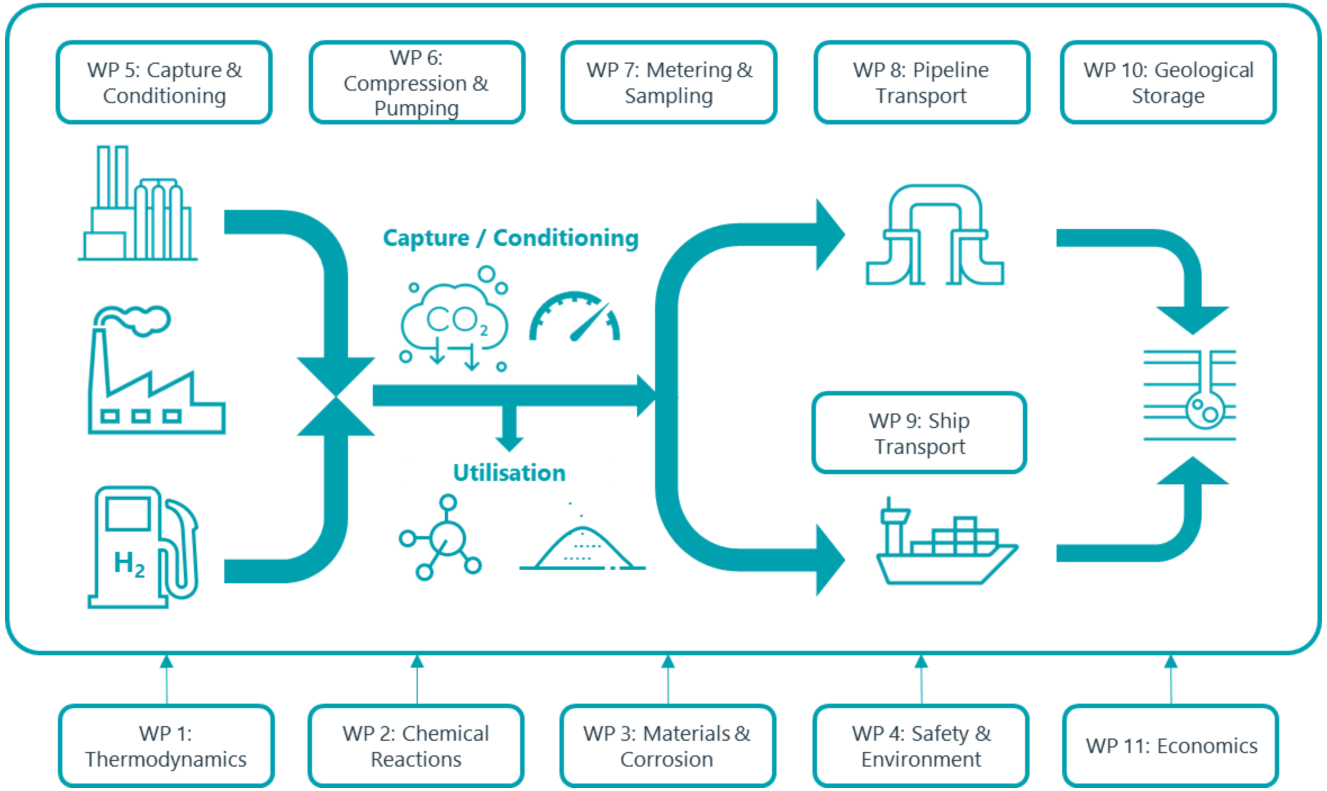
- Impurities in captured CO2 can adversely affect the material integrity, operation and injectivity in CCUS chains and impact the cost of processing and storage.
- There is limited guidance that considers the whole CCUS chain when setting the level of impurities in CO2.
- A Joint Industry Project (JIP) was therefore formed to collate current knowledge surrounding impurities and to create guidelines to support industry when setting CO2 specifications for safe and economic CCUS chains.



# Industry Guidelines for Setting the $CO_2$ Specification for CCUS Chains

Link to Industry Guidelines

- The guidelines cover the full CCUS chain from capture through to geological storage.
- The guidelines recognises the interdependence between each part of the chain and between the emitters and transport & storage operators.
- Reviews the required CO2 conditioning to meet safety, environmental, technical and operational requirements.
- The JIP collaborated with research and industry experts to provide a comprehensive and holistic understanding of the impact of impurities across the entire chain.



WP 5: Capture & Conditioning

WP 6: Compression & Pumping

WP 7: Metering & Sampling

WP 8: Pipeline Transport

WP 10: Geological Storage

Capture / Conditioning

Utilisation

WP 9: Ship Transport

WP 1: Thermodynamics

WP 2: Chemical Reactions

WP 3: Materials & Corrosion

WP 4: Safety & Environment

WP 11: Economics

# Typical Impurities (non-exhaustive)

| Component | Comment |
|---|---|
| **Water** | Causes corrosion through carbonic acid produced between $CO_2$ and water. Can form corrosive acids with SOx and NOx components. Risk of hydrate formation leading to pipeline blockages and operational/safety issues. |
| **$H_2S$** | Highly toxic. May react with other compounds to form acids and elemental sulphur. The acids have a high potential for corrosion and the elemental sulphur may lead to clogging. $H_2S$ may lead to sulphide stress corrosion cracking with water. |
| **$SO_X$ / $NO_X$** | Can react with water to a highly corrosive aqueous acid phase. |
| **CO** | Can react with other impurities to form acidic products. Risk for CO-$CO_2$ cracking if a free water phase is formed. |
| **$O_2$** | Oxygen is a cause of corrosion in wet conditions. Oxygen enhances the formation of elemental sulphur and sulphuric/nitric acid if $SO_X$/$NO_X$ are present. May result in biological growth in reservoirs and injectivity issues. |
| **$N_2$ / Ar / $CH_4$ / $H_2$** | Non-condensable 'light' substances: Ar, $CH_4$, $H_2$, $C_2H_6$ (also $H_2S$, $O_2$, CO). Can impact the phase envelope by increasing the size of the two-phase region and reduces both the density and viscosity of the CO2 stream. Reduces the molecular weight of the stream and increases compression duty. In liquids they increase the vapour pressure of the liquid which may require higher pressure to supress vaporisation. |
| **$H_2$** | $H_2$ can lower the tensile strength of steels and accelerate fatigue crack growth at relatively low hydrogen partial pressures. |
| **Amine** | Amines may react with and degrade several non-metallic materials. |
| **Alcohols / Aldehydes** | Increases the fluid dew point causing the stream to condense at higher temperatures. Potential operability issues. |

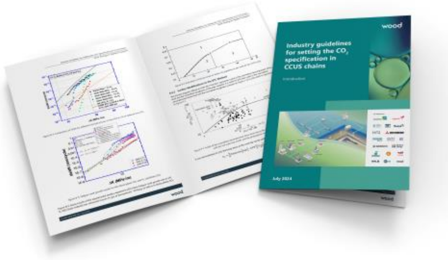
For a fuller list of impurities and impacts, refer to the guidelines

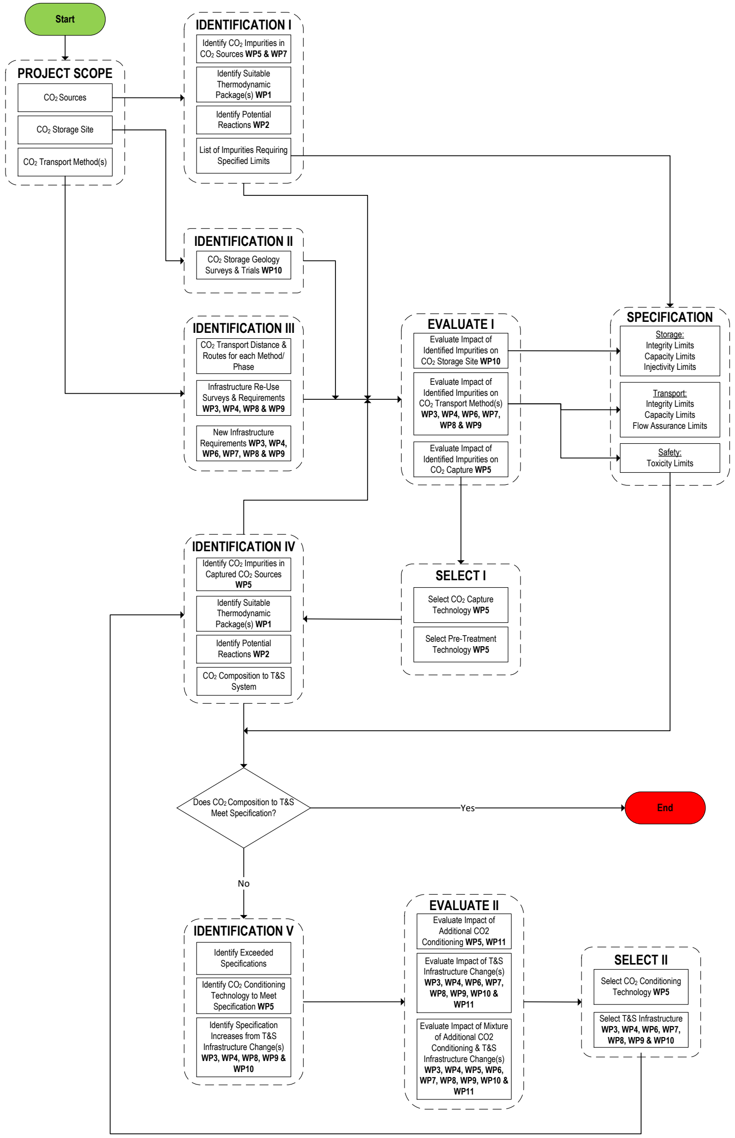
# Typical Impact of Impurities

| | |
|---|---|
| **Material Integrity:** | Impurities can directly or from reaction with other impurities, lead to corrosion and cracking / fracture issues. CO2 and impurities may not be suitable for certain non-metallic materials (i.e. polymeric materials) |
| **Phase behavior:** | The gas-liquid-water equilibrium is important to determine where water will form an aqueous phase. Gas-liquid phase boundaries are important to predict transport operations. The vapor-liquid-solid equilibrium (VLSE) is also relevant as solid depositions may well be an effect of upset conditions under certain scenarios (scale / hydrates / solid $CO_2$ / salts). |
| **Density:** | An important parameter in the dimensioning of pipelines, vessels, compressors and pumps. It is also needed for fiscal metering if the meters provide volumetric flows. In the storage reservoir a lower density of the injected CO2, will allow a lower overall mass to be stored. |
| **Speed of sound:** | Determines the flow rate in choked flow and for some types of meter calculations. It is an important parameter in the dimensioning of pipelines against running ductile fracture, leak testing practices and during the depressurization of pipelines. |
| **Viscosity:** | Impacts pressure drop in pipes, in designing processing equipment and in subsurface reservoir flow modelling. |
| **Enthalpy / JT:** | Required during $CO_2$ injection into depleted oil and gas reservoirs to determine temperature drop, material selection and risk of water drop-out in humid $CO_2$ streams. It is also required for sizing compressors, pumps and heat exchangers. |

# Introduction to the Guidelines

- Introduction to the JIP objectives and scope of the Work Packages.
- Provision of a logical workflow methodology for setting a CO2 Specification including a worked example.  Steps include:
  - Identify the CCUS chain components - source industries, transport options and reservoir type.
  - Identify the impurities from capture and pre-treatment technologies.
  - Assess impact of impurities across the chain and determine where limits are exceeded.
  - Add required conditioning processes to limit impurities and confirm introduction of any new impurities.
  - Iterate the process to determine a CO2 specification that is cost effective and meets the technical and operational requirements of the chain.





Start

**PROJECT SCOPE**

$CO_2$ Sources

$CO_2$ Storage Site

$CO_2$ Transport Method(s)

**IDENTIFICATION I**

Identify $CO_2$ Impurities in $CO_2$ Sources **WP5 & WP7**

Identify Suitable Thermodynamic Package(s) **WP1**

Identify Potential Reactions **WP2**

List of Impurities Requiring Specified Limits

**IDENTIFICATION II**

$CO_2$ Storage Geology Surveys & Trials **WP10**

**IDENTIFICATION III**

$CO_2$ Transport Distance & Routes for each Method/ Phase

Infrastructure Re-Use Surveys & Requirements **WP3, WP4, WP8 & WP9**

New Infrastructure Requirements **WP3, WP4, WP6, WP7, WP8 & WP9**

**EVALUATE I**

Evaluate Impact of Identified Impurities on $CO_2$ Storage Site **WP10**

Evaluate Impact of Identified Impurities on $CO_2$ Transport Method(s) **WP3, WP4, WP6, WP7, WP8 & WP9**

Evaluate Impact of Identified Impurities on $CO_2$ Capture **WP5**

**SPECIFICATION**

Storage:
Integrity Limits
Capacity Limits
Injectivity Limits

Transport:
Integrity Limits
Capacity Limits
Flow Assurance Limits

Safety:
Toxicity Limits

**IDENTIFICATION IV**

Identify $CO_2$ Impurities in Captured $CO_2$ Sources **WP5**

Identify Suitable Thermodynamic Package(s) **WP1**

Identify Potential Reactions **WP2**

$CO_2$ Composition to T&S System

**SELECT I**

Select $CO_2$ Capture Technology **WP5**

Select Pre-Treatment Technology **WP5**

Does $CO_2$ Composition to T&S Meet Specification?

Yes

End

No

**IDENTIFICATION V**

Identify Exceeded Specifications

Identify $CO_2$ Conditioning Technology to Meet Specification **WP5**

Identify Specification Increases from T&S Infrastructure Change(s) **WP3, WP4, WP8, WP9 & WP10**

**EVALUATE II**

Evaluate Impact of Additional CO2 Conditioning **WP5, WP11**

Evaluate Impact of T&S Infrastructure Change(s) **WP3, WP4, WP6, WP7, WP8, WP9, WP10 & WP11**

Evaluate Impact of Mixture of Additional CO2 Conditioning & T&S Infrastructure Change(s) **WP3, WP4, WP5, WP6, WP7, WP8, WP9, WP10 & WP11**

**SELECT II**

Select $CO_2$ Conditioning Technology **WP5**

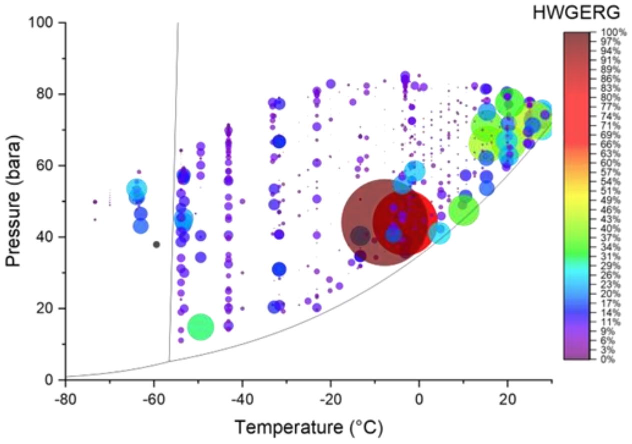
Select T&S Infrastructure **WP3, WP4, WP6, WP7, WP8, WP9 & WP10**

# WP1 – Thermodynamics

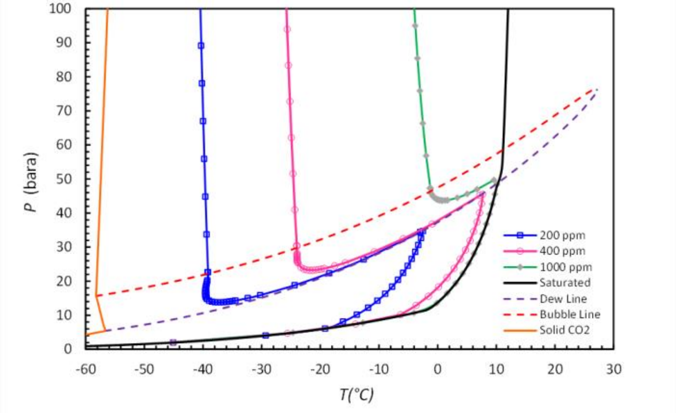
**Key Findings**

- Heriot Watt University gathered >1.5 M experimental data points from the literature for >30 impurities within $CO_2$ streams for gap analysis and validation of existing modelling methodologies.
- Reported modelling error margins for predicting the properties of interest using most advanced modelling methodologies.
- There is no single solution that provides a comprehensive solution for modeling $CO_2$ fluids. Depending on the composition, pressure, and temperature range of interest and the nature of the properties required for certain assessments, different modelling methodologies may need to be applied.
- Provided a guideline on the selection of the most appropriate modelling approach.
- Provided example thermodynamic properties for binary and mixtures to allow the end user to confirm the validity of their modelling tools.

## Availability of data and accuracy of modelling



## Example cases for validation of industrial tools



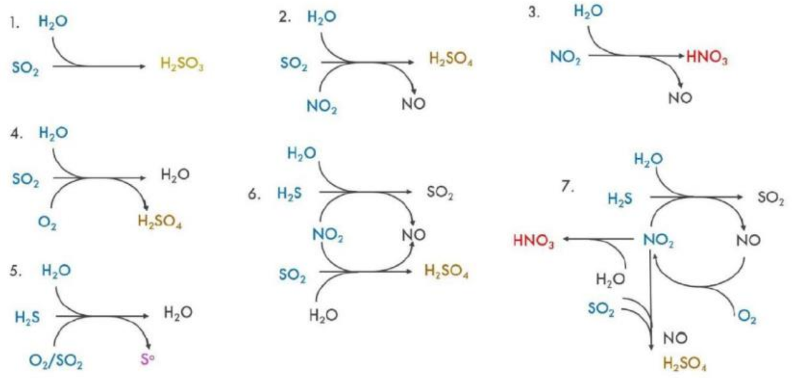
Hydrate Curves using CPA (95% $CO_2$ + 5% $CH_4$)

# WP2 – Reaction Chemistry

**Key Findings**

- Identification of typical reactions and their consequence across the CCS chain, including acid formation, acid-base, sulphur formation, which can lead to issues such as corrosion, reduced reservoir injectivity etc.
- Review of solubility and precipitation of impurities and reaction products
- Review of modelling tools. Reaction software can generally predict equilibrium behaviour of reactions, impurity solubilities in $CO_2$ and the formation of aqueous phases. However, they do not generally model reaction kinetics.
- Available experimental data is limited, and future research is required for a wider range of impurities and operating conditions.

| **Acid formation reactions** |
|---|
| $H_2O + SO_2 \rightarrow H_2SO_3$ |
| $H_2O + SO_2 + ½\ O_2 \rightarrow H_2SO_4$ |
| $H_2S + 3NO_2 \rightarrow SO_2 + H_2O + 3NO$ |
| $2\ NO + O_2 \rightarrow 2NO_2$ |
| $H_2O + NO_2 + SO_2 \rightarrow NO + H_2SO_4$ |
| $H_2O + 3NO_2 \rightarrow 2HNO_3 + NO$ |
| $H_2O + 2\ NO_2 \rightarrow HNO_2 + HNO_3$ |
| $3\ HNO_2 \rightarrow HNO_3 + 2NO + H_2O$ |
| $2\ H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$ |
| **Sulfur reactions** |
| $8\ H_2S + O_2 \rightarrow S_8 + 8H_2O$ |
| $H_2S + 2NO_2 \rightarrow 2NO + H_2O + ½SO_2 + ½\ S$ |
| $2\ H_2S + SO_2 \rightarrow 3S + 2H_2O$ |
| $H_2S + HNO_3 \rightarrow 3S + 2NO + 4H_2O$ |
| $H_2S + H_2SO_4 \rightarrow S + SO_2 + 2H_2O$ |
| **Acid-base reactions (solids)** |
| $CO_2\ (g) + 2NH_3\ (g) \rightarrow NH_4CO_2NH_2\ (s)$ |
| $Amines + CO_2 \rightarrow$ ammonium salts +++ |



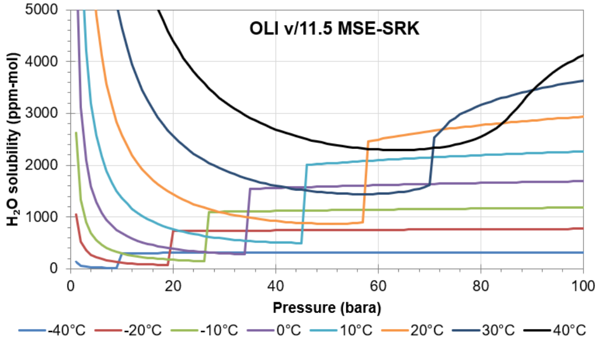
Ref: J. Sonke, B. H. Morland, G. Moulie and M. S. Franke, "Corrosion and chemical reactions in impure CO2," *International Journal of Greenhouse Gas Control,* vol. 133, no. 104075, 2024.

# WP3 – Materials and Corrosion

**Key Findings**

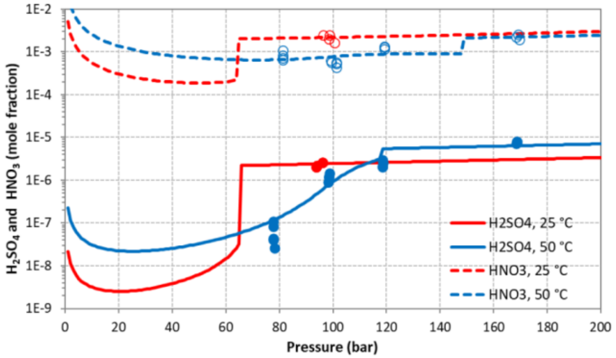
- Provided material selection and corrosion management philosophy across the CCS chain based on failure modes and effect analysis. Including impact of impurities on non-metallic materials.
- Literature review of time dependent and non-time dependent degradation mechanisms owing to impurities e.g. stress corrosion cracking, acid drop out.
- Laboratory experiments have shown $NO_X$, $SO_X$, $O_2$, $H_2S$ in $CO_2$ can cause corrosion of carbon steel to occur even when free water precipitation is not predicted (below saturation level for pure $CO_2$).
- Identified gaps and unknowns that require further research (e.g. increasing range of impurities at operating conditions and composition of liquid/solid deposition).

## Water Solubility Curves



Ref: B.H. Morland, G. Svenningsen and Arne Dugstad, "The Challenge of Monitoring Impurity Content of CO2 Streams," MDPI Processes 2021, 9, 570.

## Acid Solubility Curves



Ref: J. Sonke, B. H. Morland, G. Moulie and M. S. Franke, "Corrosion and chemical reactions in impure CO2," *International Journal of Greenhouse Gas Control,* vol. 133, no. 104075, 2024.

# WP4 – Safety and Environment

**Key Findings**

- Review of $CO_2$ safety limits and threshold data and discussion on Consequence and Risk-based assessments.
- For planned discharges industry should adhere to regulations, including short and long-term exposure limits of $CO_2$ and impurities (STEL and LTEL).
- For unplanned releases time-based approaches are preferred such as the use of probits and and Specified Level of Toxicity (SLOT) / Significant Likelihood of Death (SLOD) values.
- The use of simple dispersion models is suitable when geometry is flat and clear of obstacles, whereas CFD is recommended for complex geometries (e.g. rough terrain, presence of obstacles).
- Typical impurity levels $CO_2$ streams has minimal impact on cloud dispersion behaviour vs pure $CO_2$. Effects only observed > 5 mol%.
- Projects should assess release impacts across all safety limits for short and long-term exposure.

## Typical results from gas dispersion modelling

40,000 ppm CO2 (IDLH of CO2)

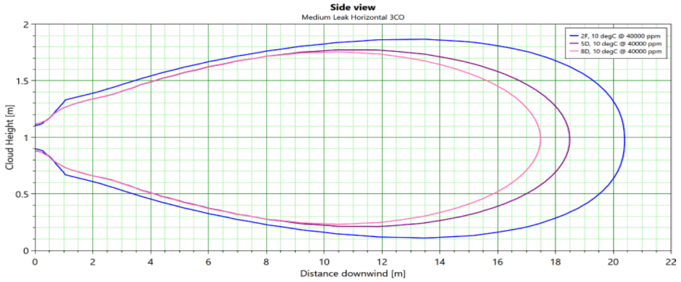


Figure 4-15: Downwind distance to IDLH $CO_2$, stream composition 97%$CO_2$, 3%CO.

1200 ppm CO (IDLH of CO)

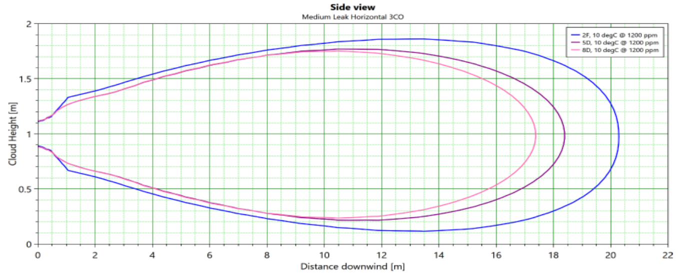


Figure 4-16: Downwind distance to IDLH CO, stream composition 97%$CO_2$, 3%CO.

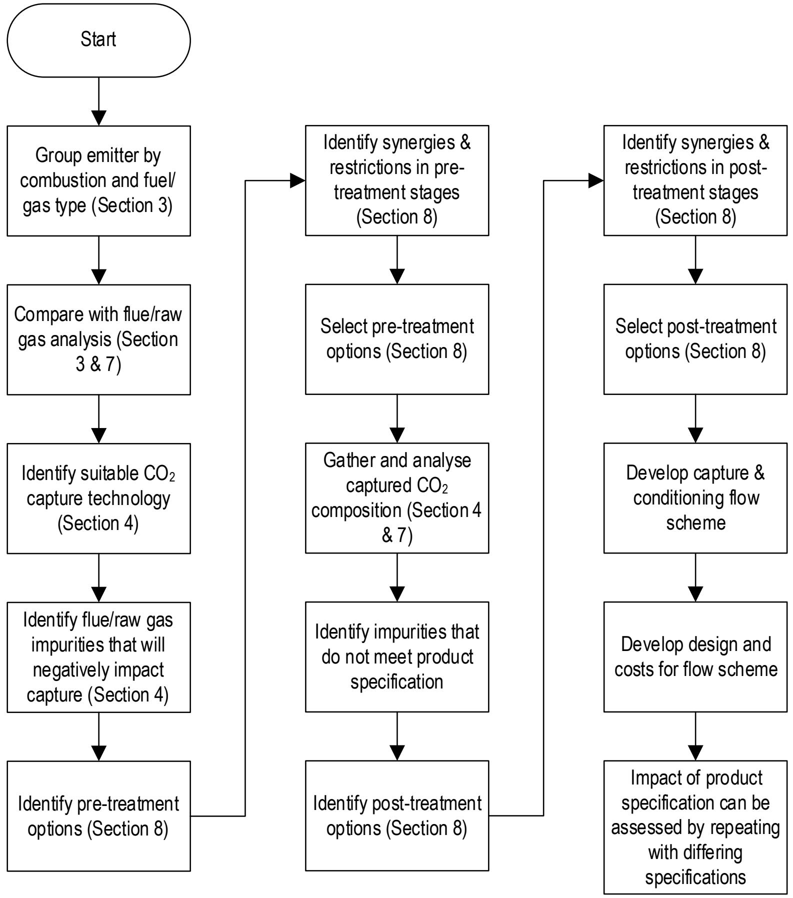
Downwind distances to Immediately Dangerous To Life or Health limits (IDLH) for CO2 and CO for stream 97% CO2, 3% CO

# WP5 – Capture and Conditioning

**Key Findings**

- Review of $CO_2$ impurities from various industries.
- Review of capture processes and impacts of impurities.
- Review of data from the Technology Centre Mongstad to determine levels of anticipated impurities in $CO_2$ at ppm levels.
- Review of impurity removal processes.
- Review of impact of impurities on liquefaction processes, storage and ship transport at various pressure levels.
- Flow chart methodology for selecting $CO_2$ treatment and liquefaction flow schemes provided.
- Flow chart methodology for selecting capture & conditioning processes, including a worked example.

## Guide to selecting capture and conditioning technologies



Start

Group emitter by combustion and fuel/ gas type (Section 3)

Compare with flue/raw gas analysis (Section 3 & 7)

Identify suitable $CO_2$ capture technology (Section 4)

Identify flue/raw gas impurities that will negatively impact capture (Section 4)

Identify pre-treatment options (Section 8)

Identify synergies & restrictions in pre-treatment stages (Section 8)

Select pre-treatment options (Section 8)

Gather and analyse captured $CO_2$ composition (Section 4 & 7)

Identify impurities that do not meet product specification

Identify post-treatment options (Section 8)

Identify synergies & restrictions in post-treatment stages (Section 8)

Select post-treatment options (Section 8)

Develop capture & conditioning flow scheme

Develop design and costs for flow scheme

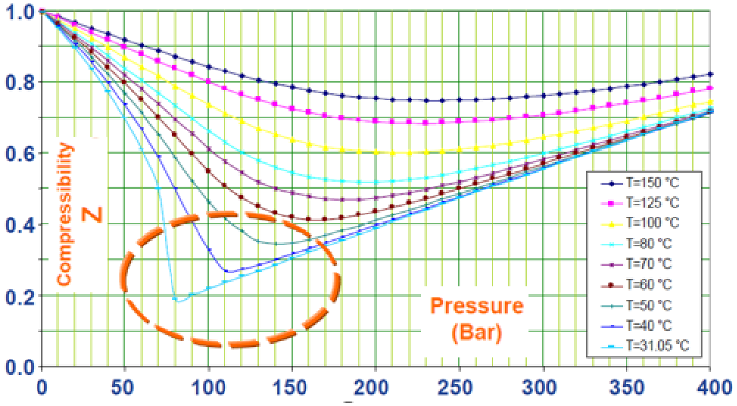
Impact of product specification can be assessed by repeating with differing specifications

# WP6 – Compression and Pumping

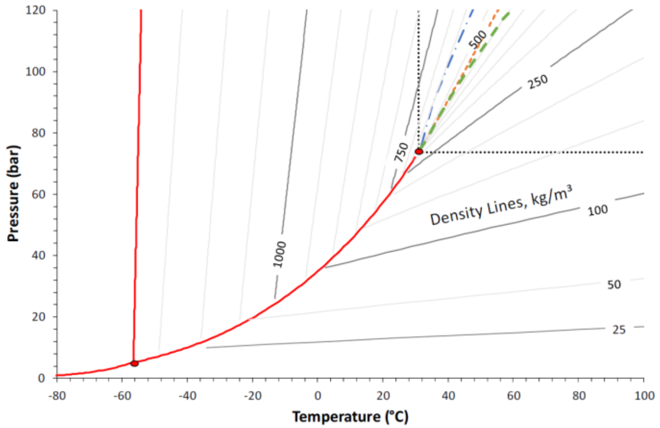
**Key Findings**

- Investigated impact of impurities on rotating equipment design and performance including engagement with equipment & seal suppliers.
- Impact of impurities on rotating machinery is primarily seen with addition of light components increasing compression duties (reduced molecular weight) and lowering boiling points requiring greater NPSH.
- Irregular behaviour of $CO_2$ may be diminished by impurities so additionally consider a pure $CO_2$ case to be conservative.
- Rotating machinery can be designed to accommodate any level of impurities so does not generally determine the $CO_2$ specification.
- Early discussion of likely impurities with equipment & seal suppliers is recommended for appropriate design and seal selection.

## Non-Ideal Behaviour of $CO_2$



Ref: GE Oil and Gas, Wadas, B., “Innovation Now” 2010



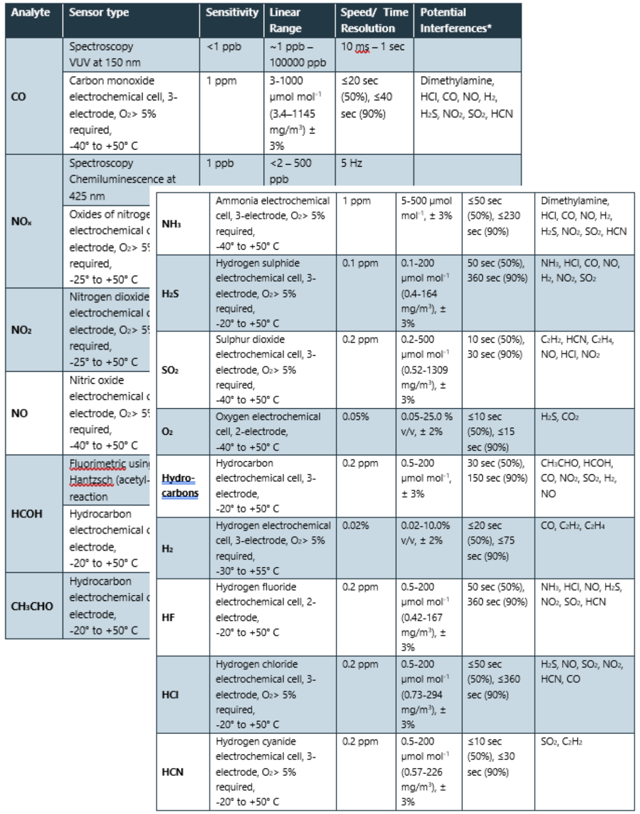
Ref: TÜV SÜD National Engineering Laboratory, “Performance of Flow Meters in Gas, Liquid and Dense Phase CO2: Test results for Coriolis meters,” 2023.

# WP7 – Metering and Sampling

**Key Findings**

- Overview of flow measurement upstream and downstream of the capture plant.
- Review and applicability of current measurement technologies and standards and practices.
- Flow meter calibration methodologies. Limited flow calibration facilities and evolving legislation are challenges to the design and operation of reliable metering solutions for CCS.
- Review of sampling methodologies and analysis techniques, identifying the challenges to monitoring impurity concentrations commensurate with network specification limits.
- Online (direct) and offline (indirect) sampling methods and challenges were discussed for various impurities. (No proven method exists for representative sampling of dense phase rich $CO_2$).
- Sampling & analysis challenges: traceable reference materials, analysers which are accurate under stream conditions, proven sample system materials, proven methods for representative sampling, proven analytical methods.

What gets measured gets managed



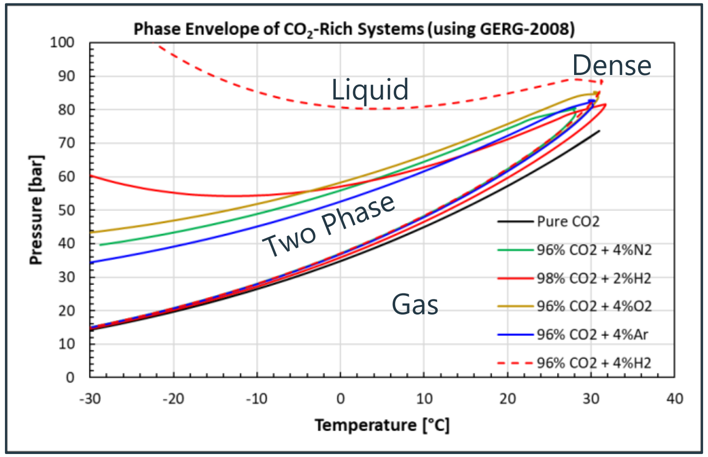
| Analyte | Sensor type | Sensitivity | Linear Range | Speed/ Time Resolution | Potential Interferences* |
|---|---|---|---|---|---|
| CO | Spectroscopy<br>VUV at 150 nm | <1 ppb | ~1 ppb – 100000 ppb | 10 ms – 1 sec | |
| | Carbon monoxide electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-40° to +50° C | 1 ppm | 3-1000 µmol $mol^{-1}$ (3.4–1145 $mg/m^3$) ± 3% | ≤20 sec (50%), ≤40 sec (90%) | Dimethylamine, HCl, CO, NO, $H_2$, $H_2S$, $NO_2$, $SO_2$, HCN |
| $NO_x$ | Spectroscopy<br>Chemiluminescence at 425 nm | 1 ppb | <2 – 500 ppb | 5 Hz | |
| | Oxides of nitroge electrochemical c electrode, $O_2$> 5 required,<br>-25° to +50° C | | | | |
| $NO_2$ | Nitrogen dioxide electrochemical c electrode, $O_2$> 5 required,<br>-25° to +50° C | | | | |
| NO | Nitric oxide electrochemical c electrode, $O_2$> 5 required,<br>-40° to +50° C | | | | |
| HCOH | Fluorimetric using Hantzsch (acetyl- reaction | | | | |
| | Hydrocarbon electrochemical c electrode,<br>-20° to +50° C | | | | |
| $CH_3CHO$ | Hydrocarbon electrochemical c electrode,<br>-20° to +50° C | | | | |

| | | | | | |
|---|---|---|---|---|---|
| $NH_3$ | Ammonia electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-40° to +50° C | 1 ppm | 5-500 µmol $mol^{-1}$, ± 3% | ≤50 sec (50%), ≤230 sec (90%) | Dimethylamine, HCl, CO, NO, $H_2$, $H_2S$, $NO_2$, $SO_2$, HCN |
| $H_2S$ | Hydrogen sulphide electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-20° to +50° C | 0.1 ppm | 0.1-200 µmol $mol^{-1}$ (0.4-164 $mg/m^3$), ± 3% | 50 sec (50%), 360 sec (90%) | $NH_3$, HCl, CO, NO, $H_2$, $NO_2$, $SO_2$ |
| $SO_2$ | Sulphur dioxide electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-40° to +50° C | 0.2 ppm | 0.2-500 µmol $mol^{-1}$ (0.52-1309 $mg/m^3$), ± 3% | 10 sec (50%), 30 sec (90%) | $C_2H_2$, HCN, $C_2H_4$, NO, HCl, $NO_2$ |
| $O_2$ | Oxygen electrochemical cell, 2-electrode,<br>-40° to +50° C | 0.05% | 0.05-25.0 % v/v, ± 2% | ≤10 sec (50%), ≤15 sec (90%) | $H_2S$, $CO_2$ |
| Hydro-carbons | Hydrocarbon electrochemical cell, 3-electrode,<br>-20° to +50° C | 0.2 ppm | 0.5-200 µmol $mol^{-1}$, ± 3% | 30 sec (50%), 150 sec (90%) | $CH_3CHO$, HCOH, CO, $NO_2$, $SO_2$, $H_2$, NO |
| $H_2$ | Hydrogen electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-30° to +55° C | 0.02% | 0.02-10.0% v/v, ± 2% | ≤20 sec (50%), ≤75 sec (90%) | CO, $C_2H_2$, $C_2H_4$ |
| HF | Hydrogen fluoride electrochemical cell, 2-electrode,<br>-20° to +50° C | 0.2 ppm | 0.5-200 µmol $mol^{-1}$ (0.42-167 $mg/m^3$), ± 3% | 50 sec (50%), 360 sec (90%) | $NH_3$, HCl, NO, $H_2S$, $NO_2$, $SO_2$, HCN |
| HCl | Hydrogen chloride electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-20° to +50° C | 0.2 ppm | 0.5-200 µmol $mol^{-1}$ (0.73-294 $mg/m^3$), ± 3% | ≤50 sec (50%), ≤360 sec (90%) | $H_2S$, NO, $SO_2$, $NO_2$, HCN, CO |
| HCN | Hydrogen cyanide electrochemical cell, 3-electrode, $O_2$> 5% required,<br>-20° to +50° C | 0.2 ppm | 0.5-200 µmol $mol^{-1}$ (0.57-226 $mg/m^3$), ± 3% | ≤10 sec (50%), ≤30 sec (90%) | $SO_2$, $C_2H_2$ |

# WP8 – Pipeline Transport

**Key Findings**

- Review of the impact of impurities on pipeline design, material selection and operation.
- Discussion on management of multi-phase flow and abnormal / transient operations.
- Discussion on impact of impurities on re-qualifying existing pipelines for $CO_2$ service.
- Assess the impact of impurities on Fatigue Degradation.
- Even at 1 mol% hydrogen may have a detrimental effect on fatigue performance of pipeline steels and welded joints as has been demonstrated for $CH_4$-$H_2$ mixtures.
- Literature review of fracture control in $CO_2$ pipelines. Discussion of limitations and developments within pipeline codes / standards and potential modifications to be made to the Battelle Two Curve (BTC) method.



Ref: https://www.sintef.no/en/software/sintef-coupled-fe-cfd-model-for-fracture-propagation-control-in-co2-pipelines/ -

# WP9 – Ship Transport

**Key Findings**

- Review of ongoing research and current project specifications in $CO_2$ shipping.
- Gap assessment in existing standards for impurities in $CO_2$ and comparison again specification requirements for food-grade $CO_2$ and LPG transport.
- Discussion on material integrity and corrosion in $CO_2$ cargo with impurities.
- Assessment of impurities on cargo handling system including pressure and boil off management, off-spec management, storage, loading, offloading and custody transfer.
- Discussion on impurities on safety issues such as venting, design rules and risks of $CO_2$ freezing.
- Further research required to improve basis for developing specifications related to corrosion, cargo handling and cargo management.

Ref: https://norlights.com/news/northern-lights-first-co2-transport-ship-ready-for-delivery

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# WP10 – Geological Storage

**Key Findings**

- Assessment of the impact of impurities on injectivity, reservoir permeability, geological reactions and caprock integrity.
- Storage asset owners are recommended to conduct:
  - a review of impurities entering the network.
  - system modelling to assess impact of impurities within the reservoir and on monitoring including full-field reservoir and geomechanical simulation
  - lab / pilot trials to assess impact of impurities on reactions, physical property changes.
- In most cases the CO2 specification will be set by other parts of the CCS chain. However, each reservoir should be assessed for a sensitivity to CO2 specification.

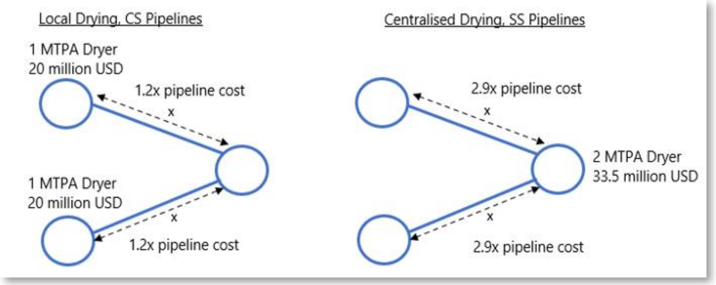
| Root causes | Relevant Impurities |
|---|---|
| Enhanced mineral dissolution | SOx, NOx, H2S, Carboxylic acids, O2, H2O |
| Enhanced mineral precipitation | SOx, NOx, H2S, O2, H2O |
| CO2 properties (density, viscosity, buoyancy) | NCs, Alcohols, HCs, Glycols, SOx, NOx, |
| Interfacial tension | Non-condensables (NC) |
| Phase boundaries | NCs, Alcohols, HCs: Supercritical/ gas transitions)<br>CH4, H2O: Hydrate formation |
| Microbial activity | O2, CH4, H2S |
| Particulates occupying pore space | Reaction products (e.g. FeCO3, Elemental S<br>Small particulates |

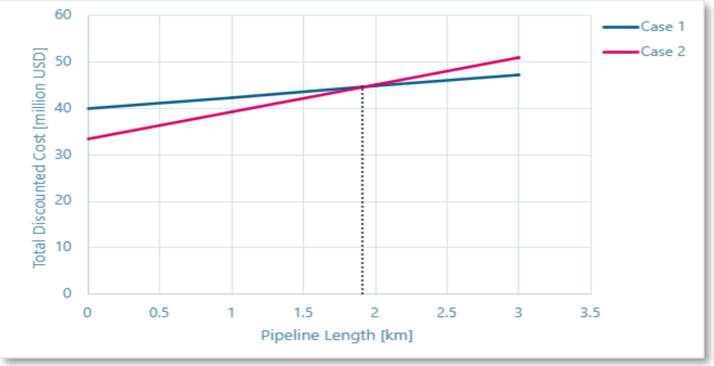
# WP11 – Economics

**Key Findings**

- Provided a recommended approach to Levelized Cost of Carbon Abatement (LCOA) / Levelized Cost of CO2 Avoided (LCCA), incorporating the impact of impurities.
- High-level costs for impurity treatment processes. CAPEX, OPEX and LCOA data are presented for:
  - dehydration
  - catalytic oxidation
  - cryogenic distillation
  - flue gas desulfurization (FGD),
  - selective catalytic reduction (SCR) processes,
  - $H_2S$ removal
  - mercury removal.
- Example provided for cost benefit analysis to study the cost of removing contaminants compared to the cost of designing the system to tolerate impurities. An example is provided to compare localised versus centralised dehydration when transporting $CO_2$ in a cluster.

$$\boldsymbol{LCOA\ (\$/MWh) = \frac{\sum_{t=1}^{t=n} \frac{Annual\ investment\ cost\ in\ year\ t}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{1}{(1+r)^t}}}$$





# Conclusions

- Setting the appropriate $CO_2$ specification for a CCUS project is a complex issue with multiple stakeholders.
- An understanding of the impacts of impurities across the whole chain is required when setting a $CO_2$ specification.
- Modelling $CO_2$ with impurities can be challenging. Benchmark against experimental data for maximum accuracy and apply sensitivities to models.
- Further research is required across thermodynamics, reaction chemistry and corrosion to cover different types and quantities of impurities across at the full temperature and pressure operating range.
- Advanced metering / calibration technologies and sampling methodologies and standards need to be developed.
- Significant growth is required in the CCUS industry to perform its key role in meeting net zero targets. The objective of the JIP guidelines is to support the industry to better understand the impact of impurities so that appropriate $CO_2$ specifications can be set to meet the safety, environmental, technical and operational requirements of the entire chain.

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