



Briefing on carbon dioxide specifications for transport

1st Report of the Thematic Working Group on:

CO₂ transport, storage and networks

Release Status: FINAL

Author: Dr Peter A Brownsort

Date: 29th November 2019

Filename and version: Briefing-CO₂-Specs-FINAL-v1.docx

EU CCUS PROJECTS NETWORK (No ENER/C2/2017-65/SI2.793333)



This project is financed by the European Commission under service contract No. ENER/C2/2017-65/SI2.793333

About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects underway across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

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Executive summary

There are two types of specification generally relevant to carbon dioxide (CO₂) transport, the product specification for end use and the requirement specification for transport. There are also two classes of transport system for CO₂ that can be distinguished, modular transport and pipeline transport.

Modular transport, using tanks carried by truck, train or ship, generally carries CO₂ as a refrigerated liquid for bulk supply to industrial and specialist gas users, including the strictly regulated food and beverage markets. Product specifications exist for a number of “pure” grades ranging from 99.5 % to 99.9995 % CO₂. Quality recommendations for the transport of liquid CO₂ are available but not widely discussed; in general, purification by the producer to meet product specifications will ensure that the requirement specification for transport is met.

Most transport of CO₂ by pipeline is for use in enhanced oil recovery (EOR), which has a relatively low quality requirement; geological storage has similar requirements. Specifications for pipeline transport generally concern the requirement for safe and effective transport in the pipeline system. There is no commonly agreed specification for CO₂ transport by pipeline. Regulations require pipeline operators to make their own assessments and set entry requirement specifications accordingly, leading to minimum CO₂ purity levels ranging between 93.5% to 96 % (or wider) with significant differences in allowed levels of other constituents.

A number of areas are identified where further information would be useful and may be available to CCUS Projects Network members to contribute through knowledge-sharing events.



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Table of Contents

1	Introduction	8
1.1	Objective and scope	8
1.2	Specification types	8
1.3	Briefing structure	9
2	Specifications for supply and modular transport of refrigerated liquid CO₂	10
2.1	Supply	10
2.2	Purity grades	10
2.3	Product specifications	11
2.4	Transport requirement specifications	14
2.5	Comparison of requirement and product specifications	15
3	Specifications for supply and transport of CO₂ by pipeline	16
3.1	Supply	16
3.2	Supply quality and specifications for CO ₂ -EOR	16
3.3	Pipeline quality recommendations.....	18
3.4	Individual project CO ₂ specifications	20
4	Summary and conclusions	22
4.1	Areas for future information gathering.....	23
5	Glossary of abbreviations and units	24
6	References.....	26



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Briefing on CO₂ Specifications for Transport

1 Introduction

This briefing follows from discussions at the CCUS Projects Network second knowledge-sharing event for members, held in the Netherlands on 16th October 2019. Discussions in the thematic working group on carbon dioxide (CO₂) transport, storage and networks suggested compilation of information on existing specifications for CO₂ would be useful to project members, and for the future work of the group.

Given the short timescale between definition of this work and the fixed delivery date for the “first thematic report” of the working group (end November 2019), this briefing is necessarily limited and should be seen as a starting point to which members of the thematic working group can add their expertise in future knowledge-sharing opportunities.

1.1 Objective and scope

The remit for this briefing is to summarise the CO₂ specifications currently in use, explain how they have come about and by whom they are used. This will include collection of example specifications in the public domain, considering how they vary and explaining the background to limits set.

The briefing is given in the context of, but not limited to, the transport of CO₂ for carbon capture, utilisation and storage (CCUS). Experience of CO₂ transport in existing supply chains will form the basis of design for current and future CCUS projects; the aim of this briefing is to inform the CCUS community on this important part of the full chain of CCUS technologies.

1.2 Specification types

A primary dictionary definition of *specification* is “An act of identifying something precisely or of stating a precise requirement” (Lexico, 2019); this definition covers two distinct types of specification, both of which are relevant to CO₂. These are the product specification and the requirement specification.

A **product specification** describes the features of a material or item that is offered by a vendor (i.e. a “sales spec.”). This may be set unilaterally by the vendor, or may be the result of negotiation with a purchaser in light of their requirement specification for a particular end use. Product specifications are in place for CO₂ currently sold by industrial gas suppliers for a range of uses.

A **requirement specification** documents a set of requirements (e.g. properties, composition etc.) that should be satisfied by a particular material or product. In the context of CO₂ transport, this relates to the requirements of CO₂ entering a transport system, such as a pipeline. The specified requirements ensure that CO₂ can be transported in the system safely, effectively and without causing damage (e.g. corrosion) to the system; this does not necessarily have any bearing on the end-use of the CO₂.

These two types of specification map broadly onto the two classes of system in use for CO₂ transport. Modular transport of CO₂ as a refrigerated liquid by truck, rail tank-car or ship is generally



associated with a product specification, although there will be a requirement specification for the transport system underlying this. Continuous transport of CO₂ as a gas or dense-phase fluid in pipelines is generally associated with a requirement specification.

1.3 Briefing structure

This briefing comprises two main sections. The first summarises product specifications existing for current commercial supplies of CO₂, which, in Europe at least, are generally transported in bulk as a refrigerated liquid using modular transport systems; it also considers the underlying requirement specification for this transport mode. The second covers requirement specifications for carrying CO₂ in pipelines, a continuous transport system. This distinction between specification types is sometimes lost, for instance, CO₂ transported by pipeline for CO₂ enhanced oil recovery (CO₂-EOR) will be covered by a pipeline entry requirement specification, but this will be essentially the same as the product specification for supply to the EOR operator; this will also be considered in the second section.



2 Specifications for supply and modular transport of refrigerated liquid CO₂

2.1 Supply

Commercial supplies of CO₂ (other than for CO₂-EOR, see Section 3 below) are generally of high purity material that is transported as a refrigerated liquid; the largest end use is in the food and beverage industries. Supplies are mostly sourced from industrial processes that have a by-product of high concentration CO₂. The main source process is hydrogen manufacture by reformation of hydrocarbons for ammonia synthesis, refinery use or merchant supply. Other sources include fermentation processes, such as for bioethanol or grain spirit, and chemical processes with a high concentration CO₂ by-product.

This market for CO₂ as an industrial gas is of the order of a few million tonnes per year in Europe, and tens of millions of tonnes globally (not including the direct combination of CO₂ with ammonia to form urea for fertilisers, which is a considerably larger usage). In Europe, the majority of supply is from large ammonia plants in Norway (Porsgrunn), the Netherlands (Sluiskil), the UK (Billingham) and a refinery in Finland (Porvoo). CO₂ is exported from these sites as a refrigerated liquid by ship to import terminals in Latvia, Sweden, Germany, Denmark, UK, France, Italy, possibly other countries, and with a new terminal under development in Ireland. From these terminals, the liquid-CO₂ is distributed to end-users either in bulk by road tanker (possibly also by rail tank-car), or in cylinders as liquid or gas. The major company involved in Europe has changed rapidly in the last few years through a series of acquisitions, mergers and divestments – Yara International to Praxair to Linde plc (Praxair-Linde merger) to Nippon Gases; other industrial gas companies also supply CO₂.

2.2 Purity grades

CO₂ has a wide variety of uses in industry with differing requirements for purity. Eleven different grades of CO₂ are listed by Praxair (2012) ranging from 99.9% to 99.9995% purity. An American measurement specialist, CO₂Meter Inc. (2019), lists nine grades associated with specific end uses, see Table 2-1.

Where grades have the same value for CO₂ purity, the specifications may differ in the impurity profiles, which may result from different source or purification processes. This may be important for certain uses, for instance beverage use, where trace impurities may strongly affect taste or smell. In the USA it seems there is a difference between beverage grade and food grade CO₂, with the latter not intended for consumption but used in packaging, processing, etc. This distinction is not made in Europe.



Table 2-1 CO₂ Purity Grades (adapted from CO₂Meter, 2019)

Grade	Purity, %
Research	99.999
Super-critical Fluid	99.998
Laser	99.95
Anaerobic	99.95
Beverage	99.9
Food	99.9
Bone Dry	99.8
Medical	99.5
Industrial	99.5

2.3 Product specifications

In the European Union, the specification of CO₂ for use as a food or beverage additive is defined in Commission Regulation (EU) No 231/2012 (EC, 2012); this specification is reproduced in Table 2-2. Note that this only gives limits for three individual constituents: minimum CO₂ content and maximum content for both carbon monoxide and oil. Other properties are covered by tests for acidity and for reducing substances. These may not be particularly useful to a prospective user who wants to know what impurities are present in the material.

Also note that the minimum CO₂ purity requirement set by this regulation is lower (at 99 %) than *any* of the supply grades indicated in Section 2.2 suggesting it is set as a safe “backstop” rather than reflecting a true requirement specification of any user.

These shortcomings are addressed by a European Industrial Gases Association document (EIGA, 2016), which provides recommended good practice for CO₂ suppliers to comply with European Commission directives and regulations, and with US Good Manufacturing Practice. It includes a more detailed and rigorous specification, reproduced in Table 2-3, with limiting characteristics and concentrations of components in CO₂ for use in food and beverages.



Table 2-2 European Commission specification for CO₂ as a food additive (EC, 2012)

E 290 CARBON DIOXIDE	
Synonyms	Carbonic acid gas; Dry ice (solid form); Carbonic anhydride
Definition	
Einecs	204-696-9
Chemical name	Carbon dioxide
Chemical formula	CO ₂
Molecular weight	44,01
Assay	Content not less than 99 % v/v on the gaseous basis
Description	A colourless gas under normal environmental conditions with a slight pungent odour. Commercial carbon dioxide is shipped and handled as a liquid in pressurised cylinders or bulk storage systems, or in compressed solid blocks of 'dry ice'. Solid (dry ice) forms usually contain added substances, such as propylene glycol or mineral oil, as binders
Identification	
Precipitate formation	When a stream of the sample is passed through a solution of barium hydroxide, a white precipitate is produced which dissolves with effervescence in dilute acetic acid
Purity	
Acidity	915 ml of gas bubbled through 50 ml of freshly boiled water must not render the latter more acid to methylorange than is 50 ml freshly boiled water to which has been added 1 ml of hydrochloric acid (0.01 N)
Reducing substances, hydrogen phosphide and sulphide	915 ml of gas bubbled through 25 ml of ammoniacal silver nitrate reagent to which has been added 3 ml of ammonia must not cause clouding or blackening of this solution
Carbon monoxide	Not more than 10 µl/l
Oil content	Not more than 5 mg/kg

The EIGA document also draws attention to the unique nature of CO₂ amongst other industrial gases, in that it is produced from many different sources and processes, each having a different potential impurity profile. It gives recommendations on establishing levels of such impurities, even when they are not included in the specification, on taking account of variability in naturally sourced CO₂ or in source processes using natural feedstocks, and on the quality assurance procedures that should be applied to liquid-CO₂ storage and supply operations. The document also notes that additional specified requirements may be negotiated between suppliers and users (EIGA, 2016).

Following from this interpretation of regulations by the industry body in Europe, commercial CO₂ suppliers will align their product specifications to comply with the EIGA specification given in Table 2-3. An example of a food grade specification closely matching this is Nippon Gases' specification "NGUK/CO₂/SPEC-0001-Liquid Carbon Dioxide – Food Grade" (Nippon Gases, 2019a).

Nippon Gases also offer a Nuclear Grade of CO₂, at a slightly higher purity (99.98% CO₂). Details given in this specification suggest a detailed negotiation has taken place to rationalise the product specification with the user's requirement specification (Nippon Gases, 2019b).



Table 2-3 Limiting characteristics for source specification for CO₂ to be used in food and drink applications (EIGA, 2016, Appendix A)

Component	Concentration						
Assay	99.9% v/v min.						
Moisture	20 ppm v/v max						
Ammonia	2.5 ppm v/v max.						
Oxygen	30 ppm v/v max.						
Oxides of nitrogen (NO/NO ₂)	2.5 ppm v/v max. each						
Non-volatile residue (particulates)	10 ppm w/w max.						
Non-volatile organic residue (oil and grease)	5 ppm w/w max.						
Phosphine ***	0.3 ppm v/v max						
Total volatile hydrocarbons (calculated as methane)	50 ppm v/v max. of which 20 ppm v/v max non-methane hydrocarbons.						
Acetaldehyde	0.2 ppm v/v max.						
Aromatic hydrocarbon	0.02 ppm v/v max.						
Carbon monoxide	10 ppm v/v max.						
Methanol	10 ppm v/v max.						
Hydrogen cyanide*	0.5 ppm v/v max						
Total sulphur (as S) **	0.1 ppm v/v max.						
Taste and odour in water	No foreign taste or odour						
Appearance in water	No colour or turbidity						
Odour and appearance of solid CO ₂ (snow)	No foreign odour or appearance						
<p>* Analysis necessary only for carbon dioxide from coal gasification sources</p> <p>** If the total sulphur content exceeds 0.1 ppm v/v as sulphur then the species must be determined separately and the following limits apply:</p> <table style="margin-left: 40px;"> <tr> <td>Carbonyl Sulphide</td> <td>0.1 ppm v/v max.</td> </tr> <tr> <td>Hydrogen Sulphide</td> <td>0.1 ppm v/v max.</td> </tr> <tr> <td>Sulphur Dioxide</td> <td>1.0 ppm v/v max.</td> </tr> </table> <p>*** Analysis necessary only for carbon dioxide from phosphate rock sources</p> <p>Where carbon dioxide complies with the specification then by definition the requirements for acidity and reducing substances as required by European Law are met.</p>		Carbonyl Sulphide	0.1 ppm v/v max.	Hydrogen Sulphide	0.1 ppm v/v max.	Sulphur Dioxide	1.0 ppm v/v max.
Carbonyl Sulphide	0.1 ppm v/v max.						
Hydrogen Sulphide	0.1 ppm v/v max.						
Sulphur Dioxide	1.0 ppm v/v max.						

The EIGA document implies that the majority of the CO₂ supply operation is geared toward the production and supply of food and beverage grade CO₂. It is assumed that higher purity grades are produced either by source processes that give inherently higher CO₂ content, or by additional purification steps tailored to the scale and purity requirements for these grades. Grades specified



with lower minimum CO₂ content may also be produced by different source processes, or may actually be supplied from the food and beverage grade.

2.4 Transport requirement specifications

There is relatively little discussion in the literature of the requirement specification for transport of CO₂ as a refrigerated liquid. This may be partly due to the long-established nature of this transport mode, but it is more likely that the operational practicalities and economics of the liquefaction process ensure that liquid-CO₂ is routinely produced at a quality well within that required for transport.

Aspelund (2010) gives a review of the literature to that time and describes CO₂ quality recommendations for transport by ship, reproduced in Table 2-4. These recommendations are based on the work of the DYNAMIS project (de Visser and Hendriks, 2007), which, however, did not consider ship transport specifically; Aspelund will have adapted the DYNAMIS recommendations in the light of his own, significant research in the field (see references in Aspelund, 2010). Requirement specifications for other modular transport systems have not been identified in the present study, it is assumed they are similar to those for ship transport.

Table 2-4 CO₂ quality recommendations for ship transport (adapted from Aspelund, 2010).

Component	Concentration	Limitation	Reason
Water (H ₂ O)	50 ppm	Design and operational considerations	Freeze-out in heat exchangers
Hydrogen sulphide (H ₂ S)	200 ppm	Health and safety considerations	Short-term exposure limit
Carbon monoxide (CO)	2000 ppm	Health and safety considerations	Short-term exposure limit
Methane (CH ₄)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Nitrogen (N ₂)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Oxygen (O ₂)	Unknown	Literature not consistent	Challenges in the reservoir
Argon (Ar)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Hydrogen (H ₂)	<0.3 % v/v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs for liquefaction
Carbon dioxide (CO ₂)	>99.7 % v/v	Balanced with other compounds	Dry ice formation



The water content recommended in Table 2-4 is well below that suggested to avoid the risk of corrosion for transport in pipelines (see Section 3 below) and is set to avoid the risk of formation of ice in the liquefaction process equipment, rather than for any issues with transport containers. The potential toxic impurities, hydrogen sulphide and carbon monoxide, have recommended maximum levels based on safe short-term exposure limits, so as not to add a (further) toxicity issue in the event of leakage (remembering CO₂ itself is toxic at high levels, not only asphyxiant).

Levels of so called “non-condensable” gas impurities (meaning those that have boiling points much lower than CO₂) are set at maximum combined total of 0.3 % by volume (v/v), which is assumed to include carbon monoxide (specified at 2000 ppm max., i.e. 0.2%) and also the unspecified oxygen. This is partly as the presence of such highly volatile impurities requires more energy, and so cost, in the liquefaction process, but also as they can shift the position of the Triple Point equilibrium compared to pure CO₂ and so lead to increased risk of dry ice (solid CO₂) formation at the low temperatures considered for liquid-CO₂ transport; dry ice formation must be avoided as it can lead to blockage of transfer lines (Aspelund, 2010). Non-condensable impurity gases are removed during the process of preparing CO₂ for transport using a distillation step, which is common to designs for preparing both refrigerated liquid CO₂ for ship transport and high pressure liquid CO₂ for pipeline transport (Aspelund, 2010).

2.5 Comparison of requirement and product specifications

It is seen that the product specifications for food and beverage grade CO₂ reviewed in Section 2.3 above are, where they overlap, more stringent than the recommended transport requirement specification in Section 2.4, also that the product specification includes limits for a wider range of impurities. It is not clear from the present brief study whether, or at what stage, additional purifications steps are added to the supply process chain, or if control is achieved through selection of CO₂ source.

Clearly, in the context of CO₂ transport for geological sequestration, this difference opens the possibility of relaxing the product specification to a closer alignment with the transport requirement specification. Given that the latter is still of high purity makes it uncertain whether this would allow any significant saving of processing costs.



3 Specifications for supply and transport of CO₂ by pipeline

3.1 Supply

The supply of CO₂ in bulk by pipeline has been established since the 1970s for CO₂-EOR in the USA and, slightly later and more limited, in Canada. Initially the supply was obtained from natural sources of fairly pure CO₂ some distance from the oilfields, which required development of pipelines to carry the CO₂ to the point of use. Later the supply was supplemented by CO₂ separated from natural gas (methane) sources and from large-scale bioethanol fermentation processes, and more recently still with CO₂ sourced by capture from power stations and industry. A review in 2015 (Wallace et al) put the total supply transported by pipeline in the USA at 68 Mt/yr, with most (79%) being from natural sources, however, the anthropogenic CO₂ proportion was predicted to increase steadily. The pipeline supply system in the USA comprises around 50 individual pipelines totalling over 7,000 km (Wallace et al, 2015).

Outside of the USA and Canada, CO₂-EOR is, or has been, operational at more limited scales in Central and South America (Mexico, Brazil), the Middle East (Saudi Arabia, United Arab Emirates), China and southeast Europe (Croatia, Romania), with limited experience of CO₂ pipelines in Brazil, the Middle East and China at least (SCCS, 2019). Transport of CO₂ by pipeline for storage, as part of carbon capture and storage (CCS) projects, is established in Norway, USA, Canada, Australia and Japan; these pipelines range from very short (< 1 km) links up to 145 km of offshore pipeline at the Snøvit facility in northern Norway (SCCS, 2019).

3.2 Supply quality and specifications for CO₂-EOR

The purity of CO₂ required for CO₂-EOR is not as high as that required for food or beverage, industrial or other specialist uses as described in Section 2 above. However, there are purity requirements for both pipeline transport and for use in EOR that have led to specifications being set that function as both requirement specification for pipeline transport and product specification for CO₂ supplied.

Considering the case in the USA, the way that the CO₂ supply for EOR developed has led to different pipeline operators defining different specifications that take account of the various CO₂ source compositions, the requirements of transport in an operator's pipeline and also the requirements of different oilfield operators. Two examples are given in Table 3-1 showing that this has led to quite wide divergence between the compositions in different supplies.

The Weyburn Field supply from the Great Plains Synfuels Plant contains a high level of hydrogen sulphide; this is acceptable in this application as the Weyburn Field already contains high levels of this impurity (UKDTI, 2002). The level might lead to a health and safety concern in event of leakage, however, this is partly mitigated as the pipeline route runs through very sparsely populated terrain.



Table 3-1 Examples of CO₂ composition and specification for supply to CO₂-EOR.

Component	Weyburn Field supply typical composition	Kinder-Morgan specification	Kinder-Morgan reason for specification
Product, carbon dioxide (CO ₂)	96 % v/v	≥ 95 %	To maintain dense phase
Water (H ₂ O)	20 ppmv	No free water; < 30 lbs/MMcf (< 630 ppm) in vapour phase	To avoid corrosion
Hydrogen sulphide (H ₂ S)	0.9 % v/v	10-200 ppm (2006) ≤ 20 ppmv (2018)	Health and safety considerations
Total sulphur (S)		≤ 35 ppm w/w (2018)	Foul odour in product
Methane (CH ₄)	0.7 % v/v	(Included in hydrocarbons)	
Hydrocarbons	2.3 % v/v (C ₂ +)	≤ 5 %, and Dew point no more than -20°F (-29°C)	To maintain dense phase of product
Carbon monoxide (CO)	0.1 % v/v	(Not specified)	
Nitrogen (N ₂)	< 300 ppmv	≤ 4 %	To maintain dense phase of product
Oxygen (O ₂)	< 50 ppmv	≤ 10 ppm w/w	Catalyst for other internal corrosion components. H ₂ S and O ₂ form elemental sulfur in EOR piping
Temperature	(Not specified)	≤ 50°C	To protect pipeline external coating
Glycol	(Not specified)	Contains no liquid glycol or ≤ 0.3 gal/MMcf	Glycol damages pump seals.

Table notes:
Weyburn supply composition is “typical composition” rather than specification (UKDTI, 2002).
Kinder-Morgan values from de Visser and Hendriks (2006) and Havens (2018), dates identified where these differ.
Water value converted from lbs/MMcf to ppm using factor (x21) from Sciencing website (2019).

The Kinder-Morgan specification allows relatively high water content. This value is higher than in the recommendations described below, but as it has been quoted over the period 2006 to 2018, is assumed to be acceptable in practice for Kinder-Morgan’s transport system (de Visser and Hendriks, 2007; Havens, 2018). This specification also appears to be lax in the levels of hydrocarbons and



nitrogen allowed, but these cannot total more than 5 % or the minimum CO₂ content would not be satisfied.

3.3 Pipeline quality recommendations

As the network of CO₂ supply pipelines in the USA developed, and as interest in CCS increased internationally, the need for a common quality standard for CO₂ for pipeline transport was recognised. This led to work within several large projects to define recommendations for the composition of CO₂ to be transported by pipeline. These included the ENCAP project, the DYNAMIS project, the CO₂PIPETRANS project and others. From these, a wide body of literature on the subject of acceptable CO₂ composition and the effect of impurities on pipeline infrastructure and downstream processes has developed, beyond the scope of this briefing, but none of this defines a general specification for CO₂ transport by pipeline.

The clearest recommendation of CO₂ composition from these projects comes from the DYNAMIS project and is given in Table 3-2.

The DYNAMIS recommendations update a number of maximum impurity concentrations from those recommended in the ENCAP project, most notably the maximum water content suggested was increased from 50 ppm to 500 ppm. This was justified on the basis that the corrosive co-contaminants present in the CO₂ streams considered by the project were low enough that they would not cause an issue with this water content. This highlights the point that these various studies were not proposing a general specification for CO₂ composition; rather they suggested acceptable composition limits for a set of project-specific assumptions.

Work in later phases of the DNV CO₂PIPETRANS project examined the issue of acceptable water content in more detail, finding that it depended on the level of acid-forming impurities, specifically sulphur dioxide (SO₂) and nitrogen dioxide (NO₂). When these were present at “moderate” levels (50-500 ppm) with water content at 500 ppm, corrosion of steel was observed. When water was present at 50 ppm, corrosion was only observed to a slight degree with NO₂ at 100 ppm (Brown et al, 2014).

This approach of defining project-specific composition limits was formalised in a Recommended Practice for the Design and Operation of CO₂ Pipelines from Det Norske Veritas, which refers to the DYNAMIS composition guidance, but recommends that CO₂ composition specifications “should be assessed from project to project” (DNV, 2010). The European Commission Directive on the geological storage of carbon dioxide similarly gives no quantification of CO₂ composition, stating only “A CO₂ stream shall consist overwhelmingly of carbon dioxide” (EC, 2009). Instead, it defines CO₂ stream acceptance criteria based on the avoidance of negative affects on storage site integrity, on avoidance of risks to health and environment, and avoidance of breaching other legislation.



Table 3-2 DYNAMIS CO₂ quality recommendation (adapted from de Visser and Hendriks, 2007)

Component	Concentration	Limitation
Carbon dioxide (CO ₂)	> 95.5 %	Balanced with other compounds in CO ₂
Water (H ₂ O)	≤ 500 ppm	Technical: below solubility limit of H ₂ O in CO ₂ . No significant cross effect of H ₂ O and H ₂ S, cross effect of H ₂ O and CH ₄ is significant but within limits for water solubility
Hydrogen sulphide (H ₂ S)	≤ 200 ppm	Health & safety considerations
Carbon monoxide (CO)	≤ 2000 ppm	Health & safety considerations
Oxygen (O ₂)	For aquifer storage < 4 % v/v; for EOR 100 – 1000 ppm	Technical: range for EOR, because lack of practical experiments on effects of O ₂ underground
Methane (CH ₄)	For aquifer storage < 4 % v/v; for EOR < 2 %	As proposed in ENCAP project
Nitrogen (N ₂)	< 4 % v/v (all non condensable gases)	As proposed in ENCAP project
Argon (Ar)	< 4 % v/v (all non condensable gases)	As proposed in ENCAP project
Hydrogen (H ₂)	< 4 % v/v (all non condensable gases)	As proposed in ENCAP project
Oxides of sulphur (SO _x)	≤ 100 ppm	Health & safety considerations
Oxides of nitrogen (NO _x)	≤ 100 ppm	Health & safety considerations

Table note: The concentration limit of all non-condensable gases together, which is O₂, CH₄, N₂, Ar and H₂, should not exceed 4 % v/v

More recently, an International Standard on *Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems*, ISO 27913:2016, has been issued which includes an appendix on the composition of CO₂ streams (ISO, 2016). This is not available publicly but from limited information in its online abstract and preview, it appears likely that a similar approach to the EC directive is taken and no clear CO₂ specification is included, although a table of “Indicative levels of main CO₂ impurities and factors driving these levels” is given (ISO, 2016).



3.4 Individual project CO₂ specifications

Following this approach of “project by project” assessment, a number of CCS projects have made their own assessments of CO₂ specification for pipeline collection networks serving proposed capture clusters. Two examples, given in Table 3-3, show that this may lead to significant differences in specification, even for different streams within a single network in the case of the CarbonNet project.

Table 3-3 Examples of pipeline entry specifications for CO₂ as defined by individual projects

Component	Teesside	CarbonNet lower	CarbonNet upper
Carbon dioxide (CO ₂)	≥ 95 % v/v	Balance of stream (> 93.5 % v/v)	100 % v/v
Water (H ₂ O)	≤ 50 ppmv	≤ 100 ppmv	≤ 100 ppmv
Hydrogen sulphide (H ₂ S)	< 200 ppmv	≤ 100 ppmv	≤ 100 ppmv
Carbon monoxide (CO)	< 2000 ppmv	≤ 900 ppmv	≤ 5000 ppmv
Oxides of nitrogen (NO _x)	< 100 ppmv	≤ 250 ppmv	≤ 2500 ppmv
Oxides of sulphur (SO _x)	< 100 ppmv	≤ 200 ppmv (SO ₂)	≤ 2000 ppmv (SO ₂)
Oxygen (O ₂)	< 10 ppmv		
Nitrogen (N ₂)	≤ 1 % v/v		
Hydrogen (H ₂)	≤ 1 % v/v		
Argon (Ar)	≤ 1 % v/v		
Methane (CH ₄)	≤ 1 % v/v		
Total non-condensable	≤ 4 % v/v	≤ 2 % v/v	≤ 5 % v/v
Hydrocarbons	≤ 2 % v/v	≤ 0.5 % v/v (other than methane)	
Particulates	≤ 1 mg/Nm ³		
Particle size	≤ 10 μm		
Ammonia	< 50 ppmv		

Table notes:
 Teesside values from (AMEC, 2015), includes additional mercury specification.
 CarbonNet values from (Harkin et al, 2016), gives a lower and upper end of a range of acceptable specifications for different streams joining the network; additional hydrogen cyanide, temperature and pressure specifications.



The approaches taken by these two projects as described in their reports (AMEC, 2015; Harkin et al, 2016) each give a good example of the considerations needed in setting a CO₂ specification for pipeline transport for an individual project. For the European context, the AMEC (2015) report gives clear derivations for the levels of individual CO₂ stream components based on both regulatory and technical considerations; both reports give good coverage of the literature and other project experience.

Considering the likely practical reality of how CO₂ pipeline systems serving CCS projects will develop in Europe (and possibly other global regions), this approach of having CO₂ quality controls being individually tailored to each project can be conceptually justified, at least in “early” years of CCS deployment in a region. Large projects making significant capital investments in CO₂ transport and storage infrastructure need to make detailed assessments of the interaction between CO₂ quality and their equipment designs to ensure their investment is well-founded, and such material compatibility studies are normal steps in the progress of large engineering projects. Equally, projects need the freedom to adapt their designs and CO₂ quality control to take advantage where cost savings can be found – provided safety standards are maintained.

These points suggest that while CCS projects using pipelines remain unconnected from each other, there is no reason to define a general CO₂ specification for pipeline transport. However, if CCS deployment advances to the point where a pipeline transport network is needed to link projects or cluster developments on an inter-regional scale, a general specification will probably be needed. At present, it is not clear whether or when this will occur; current plans indicate development of a number of capture clusters, each networked for CO₂ collection from emitters with trunk CO₂ transport to a single primary storage site, but with flexibility to transport CO₂ to a secondary (or “back-up”) storage site being provided by ship transport.



4 Summary and conclusions

There are two types of specification generally relevant to CO₂ transport, the product specification and the requirement specification. Product specifications describe composition of CO₂ offered by a supplier, usually in the context of an end use. Requirement specifications describe the composition and other properties of CO₂ needed for entry to particular system to ensure safe and effective transport. This distinction is useful to understand, but can be blurred when considering a multi-step supply chain.

There are also two classes of transport system for CO₂ that can be distinguished, modular transport and pipeline transport. Modular transport, using containers (tanks) carried by truck, train or ship, generally carries CO₂ as a refrigerated liquid under moderate pressure (e.g. -30°C, 15 bar), although other conditions are possible. Pipeline transport carries a continuous stream of CO₂ generally as a liquid or dense super-critical phase at high pressure and ambient or raised temperature (e.g. 20°C, 100 bar). These two different transport classes, and the markets they typically supply, lead to two different treatments of CO₂ specification.

Modular transport of CO₂ as a refrigerated liquid is generally used for bulk supply to industrial and specialist gas markets, the major sectors being in food and beverage use where quality standards are strictly regulated. Product specifications are set by the major suppliers in a number of “pure” grades ranging from 99.5 % to 99.9995 % CO₂, with other component concentrations typically in the order of one-to-tens of parts per million. The process of producing CO₂ as a refrigerated liquid allows opportunities to purify to these levels cost effectively; it is understood that refrigerated liquid CO₂ transported in bulk is generally of food and beverage grade, that is, 99.9% CO₂ minimum.

Although CO₂ transported by modular systems is dominated by product specifications there will be an underlying requirement specification for carriage in the tanks used, with recommendations suggesting this will allow a wider quality envelope than the product specifications. In situations where CO₂ is being transported for geological sequestration this may allow a lower level of purification with potential cost savings. It would be useful to discover the CO₂ transport requirement specification being applied to the proposed ship transport system of the Northern Lights Project (although it is understood this may be commercially sensitive); this would help other projects understand the requirements for purification in the liquefaction stage and start to set to a common standard for ship transport for CO₂ storage.

Most transport of CO₂ by pipeline is for use in EOR, mostly in the USA, with a lesser quantity carried for CCS projects and only a small amount for industrial and other use. In general CO₂-EOR has a relatively low quality requirement, based on the properties that allow CO₂ to mix with oil in the reservoir, and geological storage has similar requirements. The dominant quality concern is, then, the requirement for safe and effective transport in the pipeline and specifications relating to pipeline transport are generally of the requirement specification type.

There is no commonly agreed specification for CO₂ transport by pipeline. Regulations require pipeline operators to make assessments of what is safe to carry in their systems and set entry requirement specifications accordingly. This has led to recommendations with CO₂ purity ranging from 93.5 to 96 % (possibly wider) and a focus on the interplay between water content and acid-forming contaminants, due to their combined effect on corrosion of the pipeline material. There are



significant differences in constituent levels allowed in different recommendations as each is based on a different set of project-specific assumptions.

An International Standard is in place covering CO₂ transport by pipeline but (while not publically available) this is understood to continue the approach, also taken by the relevant EC Directive, of requiring operators to set CO₂ quality requirements for their systems individually. While there are good commercial and safety management reasons for this approach, and it suits the situation of unconnected CCS projects adequately, it may be inefficient if inter-regional connection of CCS projects becomes a reality.

4.1 Areas for future information gathering

This briefing indicates a number of areas, summarised below, where further information would be useful. It is hoped that some of this may be available to CCUS Projects Network members, to contribute through further knowledge-sharing events.

- Confirm, if possible, the quality of liquid CO₂ carried in the Nippon Gases bulk shipping system (assumed here to be food and beverage quality).
- Find out how higher and lower purity grades of liquid CO₂ are produced (additional processing, source selection, over-specification?)
- Confirm the entry requirement specification for current bulk shipping system.
- Understand what scope there is for relaxing quality of liquid CO₂ when shipping solely for geological storage; relates both to the previous point and to the liquefaction process flexibility.
- Find out what CO₂ specification is being set by Gassco for shipping in the Northern Lights project.
- Find out detail of the ISO standard, confirm the approach taken and find CO₂ stream composition detail given.
- Understand the status of any policy discussion on unifying CO₂ specifications in Europe, for pipeline or ship transport.



5 Glossary of abbreviations and units

Abbreviation	Meaning
%	per cent (assume volume basis for gases/vapours unless specified)
% v/v	per cent on volume basis
Ar	argon
bar	unit of pressure, equals 100,000 Pascals
°C	degrees Celcius
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture utilisation and storage
CH ₄	methane
CO	carbon monoxide
CO ₂	carbon dioxide
CO ₂ -EOR	carbon dioxide enhanced oil recovery
DNV	Det Norske Veritas
EC	European Commission
e.g.	for example
EIGA	European Industrial Gases Association
EOR	enhanced oil recovery
etc.	<i>etcetera</i> , and so on
EU	European Union
°F	degrees Farenheit
gal	gallons (US)
gal/MMcf	gallons (US) per million cubic feet
H ₂	hydrogen
H ₂ O	water
H ₂ S	hydrogen sulphide
i.e.	that is
ISO	International Standards Organisation
km	kilometre
lbs	pounds
lbs/MMcf	pounds per million cubic feet
max.	maximum
mg	milligram
mg/Nm ³	milligram per Normal metre cubed
min.	minimum
ml	millilitre
µm	micrometre, micron
MMcf	million cubic feet
Mt	megatonne (10 ⁶ tonnes, million tonnes)
Mt/yr	megatonne per year
N	Normal (equivalent of M = Molar for aqueous concentration)
N ₂	nitrogen



This project is financed by the European Commission under service contract No. ENER/C2/2017-65/SI2.793333

Nm ³	Normal metre cubed (for gas volume at “Normal” conditions)
NO	nitric oxide
NO ₂	nitrogen dioxide
NO _x	oxides of nitrogen
O ₂	oxygen
ppm	parts per million (assume volume basis for gases/vapours unless specified)
ppm v/v	parts per million on volume basis
ppmv	parts per million on volume basis
ppm w/w	parts per million on weight basis
S	sulphur
SCCS	Scottish Carbon Capture & Storage
SO ₂	sulphur dioxide
SO _x	oxides of sulphur
spec.	specification
UK	United Kingdom
UKDTI	UK Department of Trade and Industry
US	United States
USA	United States of America
yr	year



6 References

Note: Links are provided to websites and “grey” literature, where available. These have been checked at the time of referral or final editing, but their ongoing validity cannot be guaranteed.

AMEC. (2015). *Pipeline Network CO₂ Quality Specification*. AMEC Foster Wheeler for Tees Valley Unlimited. <http://www.teessidecollective.co.uk/wp-content/uploads/2015/07/WP5-CO2-Spec-2000-0005-DC00-SPC-0001-R1.pdf>

Aspelund, A. (2010). “Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO₂) transport.” Chapter 12 in *Developments and innovation in CCS technology*. M. M. Maroto-Valer (Ed.). Cambridge, Woodhead Publishing Ltd: 383-407.

Brown, J., Graver, B., Gulbrandsen, E., Dugstad, A. and Morland, B. (2014). “Update of DNV Recommended Practice RP-J202 with Focus on CO₂ Corrosion with Impurities.” *Energy Procedia* **63**: 2432-2441. doi: 10.1016/j.egypro.2014.11.265

CO₂Meter. (2019). *Why the Grade of CO₂ Gas you are Using is Important*. CO₂Meter Inc. Blog, October 2019, retrieved 13/11/19 from <https://www.co2meter.com/blogs/news/co2-purity-grade-oxygen-purity-grade-charts>

DNV. (2010). *Design and Operation of CO₂ pipelines*. Det Norske Veritas. <https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2010-04/RP-J202.pdf>

EC. (2009). “DIRECTIVE 2009/31/EC... on the geological storage of carbon dioxide.” *Official Journal of the European Union*. L 140/114, 5.6.2009. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF>

EC. (2012). “COMMISSION REGULATION (EU) No 231/2012 of 9 March 2012 laying down specifications for food additives listed in Annexes II and III to Regulation (EC) No 1333/2008 of the European Parliament and of the Council.” *Official Journal of the European Union*. L 83/1, 22.3.2012. European Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0231&from=EN>

EIGA. (2016). *Carbon Dioxide Food and Beverages Grade, Source Qualification, Quality Standards and Verification*. European Industrial Gases Association, Brussels. <https://www.eiga.eu/publications/eiga-documents/doc-7017-carbon-dioxide-food-and-beverages-grade-source-qualification-quality-standards-and-verification/>

Harkin, T., Filby, I., Sick, H., Manderson, D. and Ashton, R. (2017). Development of a CO₂ Specification for a CCS Hub Network. *Energy Procedia* **114**: 6708-6720. doi: 10.1016/j.egypro.2017.03.1801

Havens, K. (2018). *Pipelines – The Safest Way to Travel for CO₂*. Presentation 16.10.18, Kinder Morgan CO₂ Company. <https://lptest381.files.wordpress.com/2018/06/ken-havens-ccus-10-16-18-final.pdf>



- ISO. (2016). Online preview to *ISO 27913:2016(en), Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems*. International Standards Organisation. Retrieved 13/11/19 from <https://www.iso.org/obp/ui/#iso:std:iso:27913:ed-1:v1:en>
- Lexico. (2019). *Definition of specification in English*. Retrieved from Lexico webpage, 13/11/19. <https://www.lexico.com/en/definition/specification>
- Nippon Gases. (2019a). *NGUK/CO2/SPEC-0001- Liquid Carbon Dioxide – Food Grade*. Retrieved from Nippon Gases webpage, 21/11/19. <https://nippongases.com/uk/gases/carbon-dioxide>
- Nippon Gases. (2019b). *NGUK/CO2/SPEC-0001- Liquid Carbon Dioxide – Nuclear Grade*. Retrieved from Nippon Gases webpage, 21/11/19. <https://nippongases.com/uk/gases/carbon-dioxide>
- Praxair. (2012). *Carbon dioxide product and package information*. Retrieved from Praxair website 14/11/19. <https://www.praxairdirect.com/Specialty-Gas-Information-Center/Pure-Gas-Specifications/Carbon-Dioxide.html>
- SCCS. (2019). *Global CCS Map*, (and sources therein). Scottish Carbon Capture & Storage. Retrieved 26/11/19 from: <https://www.sccs.org.uk/map>
- Sciencing. (2019). *How to convert lbs/MMscf to ppm*. Retrieved from Sciencing webpage, 26/11/19. <https://sciencing.com/convert-lbsmmscf-ppm-8541447.html>
- UKDTI. (2002). *Carbon Dioxide Capture and Storage: Report of DTI International Technology Service Mission to the USA and Canada from 27th October to 7th November 2002*. Advanced Power Generation Technology Forum, UK Department of Trade and Industry. <https://www.apgtf-uk.com/files/missions/USCanadaMission2003/reportISMUSACanada.pdf>
- de Visser, E., Hendriks, C. (2007). *DYNAMIS CO₂ quality recommendations*. DYNAMIS Project Consortium. <https://www.sintef.no/globalassets/project/dynamis-hypogen/publications/d3-1-3-dynamis-co2-quality-recommendations1.pdf>
- Wallace, M., Goudarzi, I., Callahan, K., Wallace, R. (2015). *A Review of the CO₂ Pipeline Infrastructure in the U.S.* National Energy Technology Laboratory, US Department of Energy. http://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20A%20Review%20of%20the%20CO2%20Pipeline%20Infrastructure%20in%20the%20U.S_0.pdf

