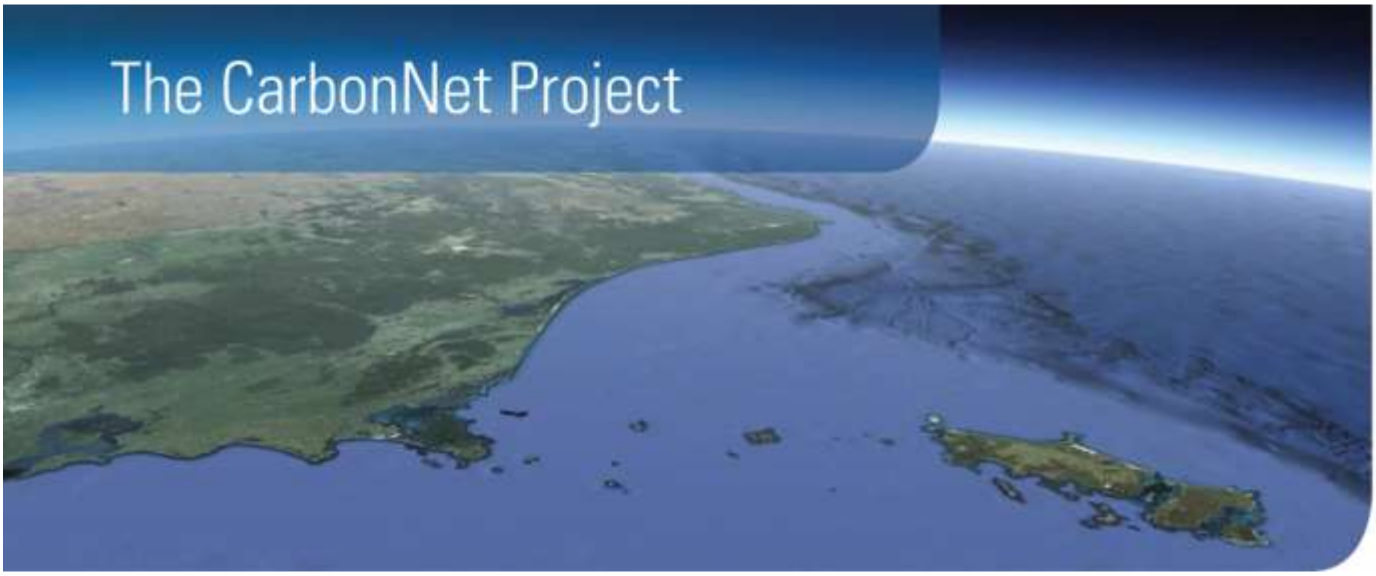

Development of a CO_2 specification for a CCS hub network

GLOBAL CCS INSTITUTE

VICTORIA State Government

Australian Government

Disclaimer

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Authorised by the Department of Economic Development, Jobs, Transport and Resources

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DEDJTR

CarbonNet Knowledge Product

DEVELOPMENT OF A CO2 SPECIFICATION FOR A CCS HUB NETWORK

MARCH 2016

WSP | PARSONS BRINCKERHOFF

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DISCLAIMER

WSP | Parsons Brinckerhoff (PB) was engaged by the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) during 2013 to 2014 to provide the CarbonNet Project with a robust technical assessment of viable transport options, including the development of designs of the preferred Transport Network components to a feasibility study level and to conduct a robust technical assessment of the potential Foundation Source and Capture projects in CarbonNet's portfolio of options, to help inform the overall CarbonNet design basis, project requirements and the business case. One of the key elements of this work was the development of a CO_2 specification for a CCS hub network, whereby the approach and outcomes are documented within this report to support knowledge sharing within the CCS global community.

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ABBREVIATIONS

AGR	Acid Gas Removal
Ar	Argon
BAU	Business as Usual
C_2H_4O	Acetaldehyde
CCS	Carbon Capture and Storage
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CS	Carbon steel
CTX	Coal to products
DEDJTR	Department of Economic Development, Jobs, Transport and Resources
FEED	Front End Engineering Design
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
HCN	Hydrogen cyanide
Hg	Mercury
MEA	Monoethanolamine
Mtpa	Million tonnes per annum
N_2	Nitrogen
NOx	Generic term for mono-nitrogen oxides NO and NO_2 (nitric oxide and nitrogen dioxide)
NPC	Net Present Cost
O_2	Oxygen
PB	Parsons Brinckerhoff
PCC	Post Combustion Capture
PM	Particulate matter
SOx	Sulphur dioxide
STEL	Short term exposure limit
TEG	Triethylene Glycol

EXECUTIVE SUMMARY

The CarbonNet Project is exploring the feasibility of a commercial scale Carbon Capture Storage (CCS) network in the Latrobe Valley, which contains one of the world's largest brown coal deposits. The CCS network will capture CO_2 from a range of source projects in the Latrobe Valley via a high pressure liquid/supercritical CO_2 pipeline to suitable storage sites in the offshore Gippsland Basin, which has greater than 31 gigatonnes of CO_2 storage potential. The network aims to service industry sources that can initially provide in the order of 1 Mtpa of CO_2 into a Foundation pipeline with a capacity of 5 Mtpa, whilst remaining scalable to support further expansion of the CCS network on a commercial basis. The development of the CO_2 specification therefore needs to take into consideration all of the requirements to ensure that the network can service multiple prospective sources and minimise barriers to entry into the network.

The CarbonNet Project, as part of its feasibility study, has developed a preliminary CO_2 specification for its carbon capture and storage (CCS) hub based network. Developing a CO_2 specification for a CCS hub network is a complex process as consideration had to be given to multiple potential source proponents each with their unique CO_2 composition (containing minor components which may impact environmental and regulatory requirements and alter the physical properties and phase envelope of the CO_2 stream), while at the other end of the network there was a limited understanding of the subsurface requirements due to undefined regulatory requirements, and specific geophysical/geomechanical limitations that were yet to be defined. These factors are key inputs to setting the transportation and storage design and determining the storage site capacity and geochemistry.

The multiple requirements and considerations of a CCS hub network influenced the philosophy adopted by CarbonNet for the CO_2 specification development which followed a risk based approach to a) minimise barriers for potential sources connecting to the network due to overly restrictive specifications and b) to minimise project costs from a whole of project perspective, not just the transport and storage components.

The approach initially involved a revalidation of the preliminary CO_2 specification prepared during the pre-feasibility stage as well as an investigation phase to understand recent developments in CCS projects and standards, the approaches that other projects had taken and to draw upon key lessons learned that would influence the design of the network and the development of the CO_2 specification. Information was gathered from a range of relevant sources, recognising available literature such as the Dynamis CO_2 Quality study report, published FEED Studies from the UK CCS competition and understanding the status of research and developments in this area.

After a comprehensive understanding of the developments in CCS projects, consideration was given to the limitations imposed by the whole of project including requirements of the subsurface, the pipeline integrity, health, safety and environment (during planned and unplanned releases) and the source proponents' requirements. This involved an assessment of the range of indicative CO_2 stream compositions from potential CO_2 source industries that may feed into the network. In particular the differences between the technology groups, i.e. post-combustion, pre-combustion and oxyfuel capture from sources that include electricity generation or a range of products from coal.

Technically achievable, business as usual limits for the various sources were identified to highlight the level of minor components that may be in the CO_2 stream with minimal additional cost implications to the source proponents above those required for CO_2 capture. The future acceptance of the proposed specification by source proponents by targeted assessments of likely compositions to be managed was also investigated.

A number of trade-off studies were completed to assess the whole of project cost implications on the specification of the water content, the pipeline operating pressure and the minimum purity requirements. Concept level commercial considerations were reviewed for cost recovery of increased transport and storage costs associated with lower purity CO_2 and/or higher levels of specific minor components.

The proposed CarbonNet CO_2 specification has a lower and upper bound for most minor components. Marginal cost analysis of the impact between the lower and upper bounds of the CO_2 specification may be completed to assist in determining the components that influence the total cost so that the CO_2 specification is as accommodating as possible to all prospective sources. Further consideration of potential source projects has identified a number of component limitations where techno-economic analysis of the trade-off between additional processing for the CO_2 sources and the impact on transport and storage would be beneficial. Assessment of the system acceptability of the preliminary specification will need to be completed in the next stages of the project, with a particular focus on understanding the implications of the proposed limits from a health, safety and environment perspective during planned (venting) or unplanned (emergency) release events

CarbonNet adopted a risk based approach to develop the preliminary CO_2 specification as the project is a hub based network that intends to minimise the barriers for entry for prospective sources. The specification provides a basis for potential sources to analyse and discuss technical and commercial implications for their CO_2 stream feeding into the network. The preliminary specification will require refinement at later stages of project to meet the requirements of regulators, design limitations and/or commercial arrangements between source proponents and the transport and storage owner in the next stages of the project.

1 INTRODUCTION

1.1 The CarbonNet project

The CarbonNet Project's vision is to develop a commercially viable CCS hub that provides a safe, competitive, flexible solution for Victoria to deal with its future carbon emissions from fossil fuels and support economic development opportunities, in Gippsland.

CarbonNet is exploring the feasibility of a commercial scale CCS network delivering CO_2 captured from a range of source projects in the Latrobe Valley, which contains one of the world's largest brown coal deposits, via a high pressure liquid/supercritical CO_2 pipeline to suitable storage sites in the offshore Gippsland Basin, which has greater than 31 gigatonnes of CO_2 storage potential. The network aims to service industry sources that can initially provide in the order of 1 Mtpa of CO_2 into a Foundation pipeline with a capacity of 5 Mtpa, whilst remaining scalable to support further expansion of the CCS network on a commercial basis. The CO_2 specification therefore needs to be cognisant of the requirements to ensure that the network can service multiple prospective sources and does not discourage or prevent users from connecting into the network due to a very tight or restrictive CO_2 specification. This needs to be achieved whilst minimising the whole of project costs (i.e. costs across the entire CCS chain).

The current development plan for CarbonNet includes:

- an Appraisal phase for the storage site, consisting of a range of activities to prove storage reservoir performance and build public confidence
- a Foundation phase comprising a transportation network capacity of 5 million tonnes per annum (Mtpa) with 125 million tonnes (Mt) sequestration capacity to service a number of CO_2 sources; and
- a subsequent Expansion phase where the ultimate capacity is determined by commercial drivers.

The proposed foundation network will comprise:

- geological CO_2 storage reservoir(s) providing sufficient capacity and integrity for long term storage of compressed CO_2;
- a foundation source/sources that provide in the order of 1 Mtpa of CO_2;
- a scalable CO_2 transportation pipeline that supports the initial capture plant(s) with additional capacity to support expansion of the CCS network on a commercial basis; and
- a commercial platform which facilitates initial investment in the foundation network and the future expansion and commercialisation of the CCS network.

The network intends to possess the capability to initially capture, transport and store anticipated carbon emission volumes in the order of one to five million tonnes per year from 2025 or earlier as part of the foundation network and with capability of expansion thereafter through the introduction of multiple CO_2 capture sources and multiple storage basins in offshore Victoria. Refer to Figure 1-1 which presents the Area of Interest for the CarbonNet project.

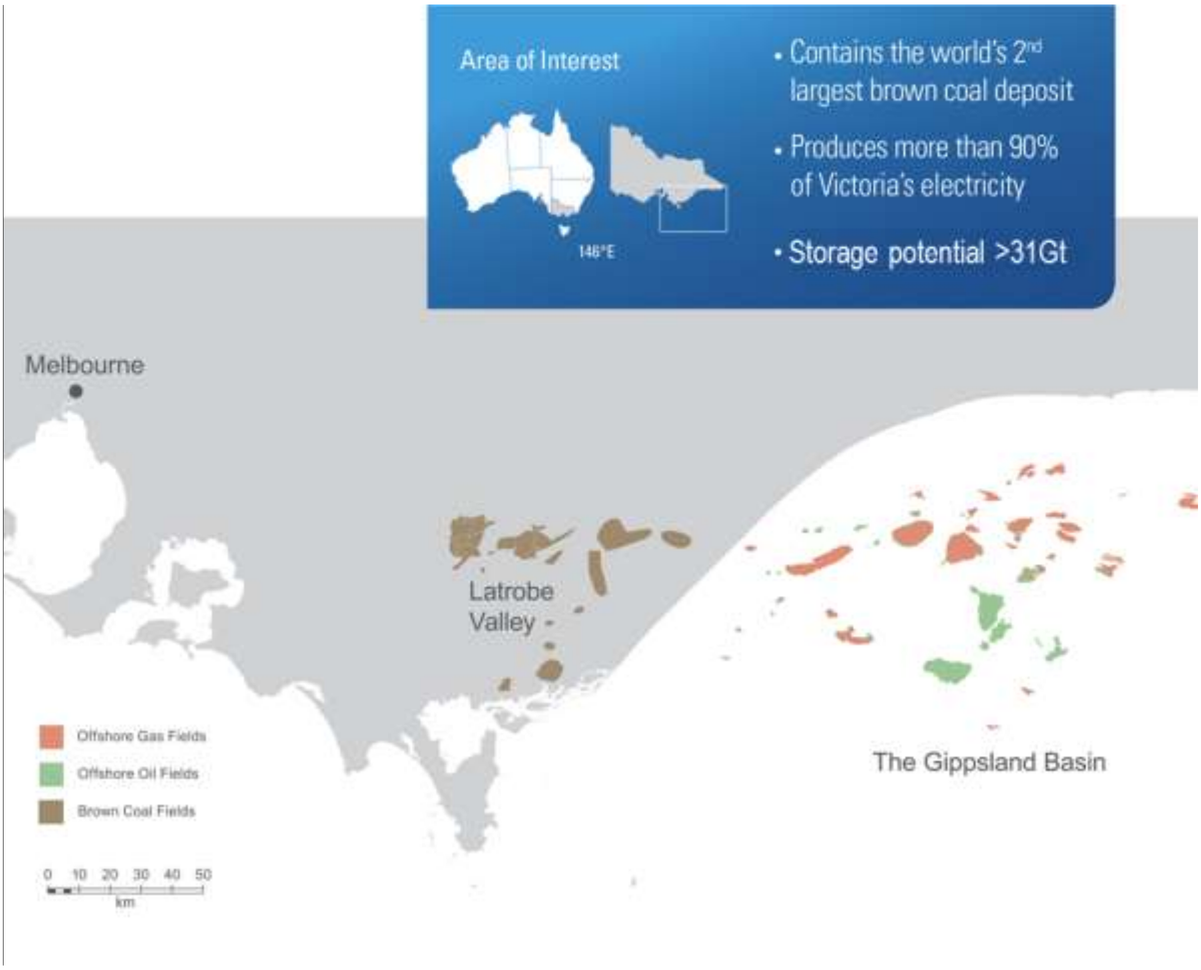

Figure 1-1 CarbonNet Project Area of Interest

1.2 Purpose of this report

The purpose of this report is to document the development of the CO_2 specification for a CCS hub network that occurred as part of the feasibility study for the CarbonNet Project, whereby the key project drivers were to ensure that the network can service multiple prospective industry sources and does not discourage or prevent users from connecting into the network due to a very tight or restrictive CO_2 specification. This report describes the risk based approach for dealing with the multiple requirements, and is intended to support knowledge sharing within the CCS global community, and increase the public and local communities understanding of broader issues associated with transporting CO_2 for CCS projects.

2 CO_2 SPECIFICATION DEVELOPMENT FOR A CCS HUB NETWORK

2.1 Introduction

The long term vision for the CarbonNet project is a multi-user network project – taking CO_2 from a range of industry sources and cost-effectively transporting this CO_2 via a pipeline network for sequestration in the offshore Gippsland Basin. Possible future source projects include:

- Existing or new coal-fired power plants operating with CO_2 capture using:
  - Post-combustion capture
  - Pre-combustion capture
  - Oxyfuel
  - Chemical looping
- Coal to products including, fertilisers, synthetic fuels, chemicals or hydrogen with CO_2 capture
- CCS from natural gas processing
- Natural gas or biomass fired power stations with CO_2 capture[1]

The CO_2 captured from the potential future source projects above is likely to comprise more than 90 % CO_2 and typically the stream will consist of other minor and trace gas components, depending on the type of feedstock and its composition, the capture technology and the solvents or amines deployed, as well as the extent of the downstream clean-up or removal technology deployed. Hence the design of the network pipeline and the development of the CO_2 specification had to consider a range of possibilities in order to align with the project drivers.

2.2 Project drivers

CarbonNet recognised the importance of developing a hub (i.e. industry cluster) based network to ensure economies of scale can be established and to lower the commercial barrier for entry for new source and capture projects. This influenced the philosophy adopted by CarbonNet for the CO_2 specification development to use a risk based approach to align with the key project drivers:

1. **To not discourage or prevent users from connecting into the network due to a very tight or restrictive CO_2 specification, and**
2. **To minimise whole of project cost (not just focusing on minimising the cost for the transport component) – but considering the whole of project across the entire CCS chain, including storage and the implications on the source and capture proponents.**

2.3 Existing body of knowledge for CO_2 specification development

Prior to the development of the CO_2 specification, CarbonNet dedicated time to investigate and understand recent developments in CCS projects, guidelines and standards. CarbonNet recognised the value in understanding the approaches that other projects had taken and to draw upon key lessons learned that would influence the design of the network and the development of the CO_2 specification.

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[1] While this and chemical looping are recognised as potential sources, they were not explicitly considered within the CO_2 specification development and therefore the implications of these have not been addressed within this report.

Some of the key reference sources considered included Appendix BB of Australian standard AS 2885.1 [1], DNV's Recommended Practise DNV-RP-J202 - Design and Operation of CO_2 pipelines [2], The World Resource Institute's (WRI) CCS guideline [3], Dynamis CO_2 Quality Recommendations [4], Vattenfall's CO_2 Quality Requirements for a system with CO_2 capture, transport and storage [5], DRET CCS Task Force Support, Carbon Dioxide Specification Study [6] and the published FEED study reports from UK CCS competition 1 [7], Department of Energy and Climate Change (DECC), United Kingdom.

Following the review of relevant literature sources it was clear that the impact of large-scale injection of co-constituents with CO_2 is currently unknown and the threshold for impurities to be injected is unknown. As can be expected the considerations are on a case by case basis (project by project), dependent on local regulations, feedstocks, source industries, capture technologies and storage site characteristics. However the reference sources provided valuable knowledge and insights to the development of the CO_2 specification for the project. Some of the key points which helped inform CarbonNet's approach are summarised below.

- DNV's recommended guidance for CO_2 stream composition was defined as 'The acceptable amount of other chemical components relates to techno-economic optimization not limited to the pipeline but including the facilities at the pipeline upstream and downstream battery limits'. [2]
- The World Resource Institute's CCS guideline recommends 'CO_2 pipeline design specifications should be fit-for-purpose and consistent with the projected concentrations of co-constituents, particularly water, hydrogen sulphide, oxygen, hydrocarbons and mercury.' [3] While the U.S. Department of Transportation's (DOT's) Office of Pipeline Safety (OPS) defines 'pipeline CO_2 as a fluid consisting of more than 90% CO_2 molecules compressed to a supercritical state, with no established standard for the permitted levels of impurities in CO_2', EOR pipeline operators have been operating for decades adhering to CO_2 concentration typically in the region of 95-99%. Facilities in Canada have been disposing of acid gas – H_2S with CO_2 through injection into deep saline aquifers and depleted hydrocarbon reservoirs geological formations since 1989. Levels of H_2S being disposed varies between 5% and 97% mole fraction, with the balance comprising mostly of CO_2. Key considerations are similar to CCS projects - 1) confinement of the injected gas; 2) effect of acid gas on the rock matrix; 3) protection of energy, mineral and groundwater resources; 4) equity interests; and 5) wellbore integrity and public safety.
- The Dynamis project published a report on its CO_2 Quality recommendations. The European Project DYNAMIS was a coordinated research program aiming to prepare for large scale production of hydrogen and electricity from decarbonised fossil fuels and recommended 'a CO_2 composition from a transport perspective and to a certain extent also from a storage perspective.' This study investigated maximum allowable concentrations of impurities in the CO_2 in order to safely transport and store it underground. Recommendations on the quality of CO_2 are given from a transport perspective mainly.' [4]
- The Vattenfall paper raised the opportunity of co-capturing other main impurities such as H_2S and SOx for storage with the CO_2 to remove other waste components to reduce flue gas clean up equipment versus the risk of the negative effect of the impurities from a technical, environmental and health perspective resulting in removal and increased costs for purification. One of their concluding statements of note was that.. 'Excessively strict requirements on CO_2 quality should be avoided to reduce costs of capture….. and from an engineering perspective, available purification and dehydration technologies should be scanned in order to find the most cost effective methods that may reach certain technical requirements well within reasonable economic limits.' [5]

At the time of CarbonNet's feasibility study in 2012/13 and the development of the CO_2 specification, E.On's Kingsnorth and Scottish Power's Longannet projects (as part of the UK's 1st CCS competition) had completed and published their FEED studies. Both projects were point to point projects (i.e. from a nominated source to a nominated sink) with a known feed composition and constraints at the offshore injection point. Hence both had a prescriptive and definitive CO_2 composition to suit.

E.On Kingsnorth critical components were H_2O and O_2. The water limit of 24 ppmv was established to avoid the formation of hydrates in the offshore facilities, while the oxygen limit of 200 ppmv was to avoid oxygen-induced corrosion in the presence of water. The oxygen limit was relaxed on the basis of the tighter water limit.

Scottish Power, Longannet similarly was a point to point project planning to capture CO_2 emissions from Longannet Power Station in Fife, Scotland and transport the CO_2 in gaseous phase (onshore) and supercritical/liquid phase (offshore) via existing gas pipelines to store in a depleted gas field known as Goldeneye. The proposed CO_2 specification required a relatively pure stream with minimum 99 mol% CO_2, and maximum 50 ppmv water, 1 ppmv oxygen (amongst other limits). These limits were “defined by the technical requirements of the transportation and injection systems and by chemical requirements of the storage reservoir”. [7] For example, given the constraint of working with the existing pipelines, the level of the diluents N_2 + CH_4 + H_2 + Ar was limited to 1 mol% and H_2 to 0.3 mol%) to manage potential fracture behaviour. It was noted that the CO_2 composition development and specification would continue post-FEED.

In the cases mentioned above, there was one known source with a defined CO_2 stream composition, and the CO_2 quality requirements were dictated by the constraints imposed by the transport network pipeline and the limitations at the nominated storage site.

Finally the International Standards Organisation (ISO) established a Technical Committee (TC265) to progress the standardisation of CCS across its entire chain through development of a number of standards. This would include the quality of CO_2 streams as part of the scope of the Capture Working Group, as well as the requirements of CO_2 streams, including composition, concentration and phase behaviour (defining transport envelope), health and safety (HSE) aspects specific to transport as part of the scope of the Transport Working Group [10]. The outcome will be a standard(s) which will include a prescriptive document for defining a CO_2 specification whereby its application is largely voluntary.

CarbonNet acknowledges that there is a solid foundation of work that has already been completed with over 6000 km of CO_2 transporting pipeline in operation and new knowledge constantly acquired. CarbonNet also acknowledges the progress of the ISO standards which may lead to a more prescriptive approach for specifying CO_2 compositions. However, CarbonNet is one of the formative hub based projects, designing for multiple potential CO_2 sources from the outset. This compelled the project to systematically investigate the entire CCS chain, including all potential source proponents to understand the real requirements and to adopt a risk based approach to defining the CO_2 specification with techno-economic considerations/optimisations to meet the projects drivers.

2.4 Proposed CO_2 specification

The CO_2 specification developed during the Feasibility Study for the CarbonNet CO_2 transport network is presented in Table 2.1. Whilst additional analysis will be required in the next (Front End Engineering and Design (FEED)) stage, it is considered that this specification provides flexibility for future potential source projects to connect to the network, minimises whole of project costs and limits the impurity range sufficiently to avoid their more severe impacts.

The proposed specification requires further analysis to determine the acceptability of the proposed limits to the CCS system.

Table 2.1 Proposed CO_2 specification

COMPONENT	UNITS	LOWER	UPPER
CO_2	vol%	Balance of stream (> 93.5)	
H_2O	Max. ppmv		100
N_2	Max. vol%	2 (total non-condensables)	5 (total non-condensables)
H_2	Max. vol%		
Ar	Max. vol%		
O_2	Max. vol%		
CH_4	Max. vol%		
CO	Max. ppmv	900	5000
H_2S	Max. ppmv	100	100[2]
SO_2	Max. ppmv	200	2000
NO_x	Max. ppmv	250	2500
HCN	Max. vol%	Subject to materiality threshold[3]	
Other hydrocarbons	Max. vol%	0.5% on total "Other Hydrocarbons"	
Temperature	°C	Critical Point[4]	50
Pressure	bar	(Subject to hydraulic modelling and the location of the CO_2 source)	

Note: It is CarbonNet's intention to retain an envelope specification to allow a range of potential sources to participate and an appropriate pricing mechanism to be developed.

Arguably, from a capture perspective, the upper limits are preferable as it allows more design choices and more flexible operation and are likely to result in a lower overall cost of capture which would improve the economic viability of the capture process. However, from a whole of project perspective this may not be the case. In each instance a trade-off study should be completed to allow the most economically viable options to be identified, rather than prescriptive limits to be set.

The following section details the approach and methodology taken, including key considerations and constraints to arrive at the specification presented above.

[2] Studies subsequent to the pipeline Feasibility Study note the potential to relax to at least 150 ppmv.
[3] A materiality threshold is proposed for all Minor Components. The threshold proposed is Australian STEL values. Those Minor Components exceeding the STEL are to be considered on a case by case basis from a Health and Safety perspective.
[4] Adopted for the Feasibility Study, however lower operating temperatures would be acceptable given the pipeline is maintained at supercritical pressures (such that the stream properties would change only gradually with temperature and would not enter the two-phase region).

3 CO_2 SPECIFICATION DEVELOPMENT

The development of the CO_2 specification and the consideration of impurity levels was a critical part of the feasibility study for the CarbonNet network. The presence of impurities or trace components within the CO_2 streams may impact environment and regulatory requirements. It may also cause a significant change to the phase envelope of the stream, which in turn impacts on the pressure envelope within which the dense phase pipeline can operate, the supercritical fluid density, the pipeline capacity and power requirements. The impurity level also impacts the storage site capacity and geochemical response. Therefore all of the components (elements and compounds likely to be present in the CO_2 stream from the identified potential sources) and the potential implications of each component on the CO_2 stream were considered. The overall methodology used to develop the CO_2 specification is described below.

3.1 Methodology

It was recognised that developing a CO_2 specification for a CCS hub network was complex, as consideration had to be given to multiple potential source proponents each with their unique CO_2 composition, while at the other end of the network there was, at the time, a limited understanding of the subsurface requirements due to undefined regulatory requirements, and specific geophysical/geomechanical limitations that were yet to be defined. Therefore the general methodology to defining the CO_2 specification, outlined in Figure 3-1 followed a risk based approach with techno-economic considerations rather than being overly prescriptive, in order to determine an optimal and cost-effective specification.

The approach initially involved a revalidation of the preliminary CO_2 specification prepared during the pre-feasibility stage as well as an investigation phase to understand recent developments in CCS projects, standards and guidelines, understand the approaches that other projects had taken and to draw upon key lessons learned that would influence the design of the network and the development of the CO_2 specification. Information was gathered from a range of relevant sources as presented in section 2.3.

Consideration had to be given to the whole of project constraints, which included the requirements at the storage site, requirements for the safe design and operation of the pipeline (including planned and unplanned releases) and the requirements of the source and capture project. Guidance on geological storage characteristics, injection requirements and constraints was sought from the CarbonNet storage team, as well as health safety and environment guidance on the presence of and limits of trace components such as H_2S, and CO within the CO_2 stream. Indicative CO_2 compositions for various capture technologies were collated from pre-feasibility studies prepared by source and capture proponents, as well as publically available information on international projects in development to understand the range of CO_2 stream compositions that the CarbonNet network could potentially service.

Each of the components were considered in isolation, giving consideration to the primary drivers for limiting the component, the guidance from a storage site and health and safety perspective and what was considered technically achievable as part of business as usual at the source and capture end. A very high level techno-economic trade off assessment associated with particular parameters from a whole of life and whole of project perspective was undertaken whilst ensuring alignment with the project's commercial drivers. This involved definition of the facilities (and associated costs) of equipment that is commercially available that would need to be installed at proponent source plants (water or sulphur removal, compression or liquefaction etc.) to reduce respective components to a certain level.

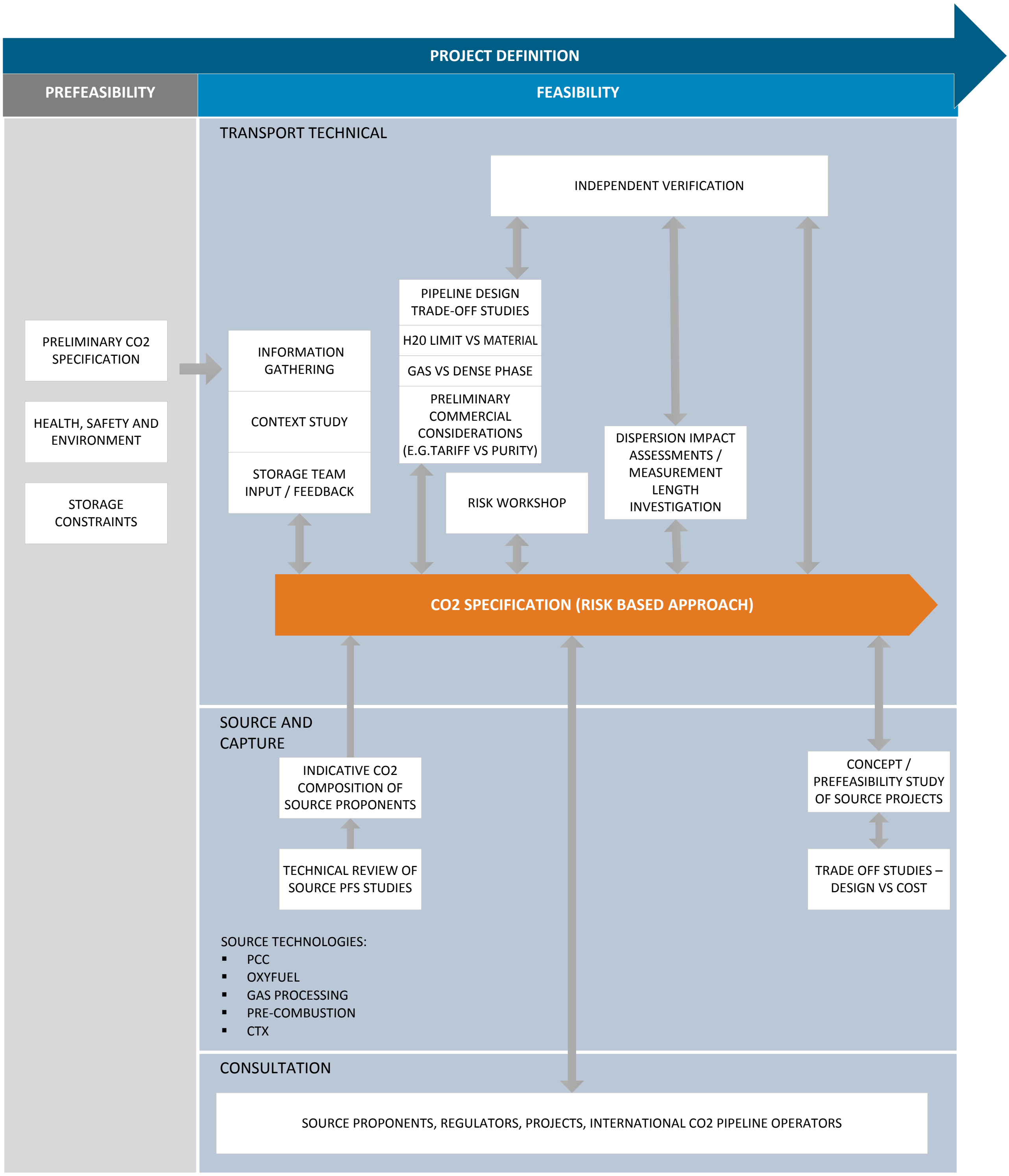

Figure 3-1 Summary of approach

3.2 Pre-feasibility study

During the CarbonNet Transport Pre-feasibility Study an initial CO_2 specification was defined. The objective at the time was to avoid unnecessarily constraining the CO_2 source projects under consideration. The identified potential source projects utilised either pre-combustion and post combustion capture, while oxy-fuel projects were considered unlikely to contribute and therefore were excluded from the development of the CO_2 specification. The CO_2 specification proposed during the pre-feasibility study for the CarbonNet CO_2 transport network is presented in Table 3.1.

Table 3.1 Proposed CO_2 specification

COMPONENT	UNITS	VALUE
CO_2	Min. vol%	97.5
H_2O	Max. ppmv	100
N_2	Max. vol%	0.8
H_2	Max. vol%	0.8
Ar	Max. vol%	0.2
HCN	Max. vol%	0.002
O_2	Max. ppmv	200
CO	Max. ppmv	2000
CH_4	Max. ppmv	500
H_2S	Max. ppmv	200
SO_2	Max. ppmv	100
NO_x	Max. ppmv	100
Other hydrocarbons	Max. vol%	2

The specification gave consideration to the known potential sources, potential impacts on storage reservoirs and identified tolerance limits for residual constituents. Whilst the CO_2 specification was determined, the primary objective was to provide a design point for the study which was technically acceptable and would not unnecessarily exclude any of the identified prospective source projects.

As the definition of the CarbonNet Project progressed towards the feasibility stage, including consideration of commercial models, it was evident that a more flexible yet technically and commercially accurate means of assessing and limiting CO_2 composition was necessary.

3.3 CarbonNet's requirements for the development of the CO_2 specification in the Feasibility study

The pre-feasibility study established an initial CO_2 specification. CarbonNet's objective of the feasibility study phase was to robustly validate the specification against the most up to date power generation and process industry information available and whole of project strategic considerations. The further development of the specification was to provide a basis to address:

- volumes, pressures and temperatures from entry points to injection well heads
- operational considerations of mixing sources and transient conditions
- geological storage characteristics including both physical and chemical interactions for a range of highly ranked potential storage sites

In formalising the specification a techno-economic trade off assessment associated with particular parameters from a whole of life and whole of project perspective was required whilst ensuring alignment with the project's commercial drivers. In undertaking this task the definition of the following items were required:

- facilities (and associated costs) that would need to be installed at proponent source plants (water or sulphur removal, compression or liquefaction etc.)
- equipment (and associated costs) that would be installed as part of CarbonNet Transport Network (if any).
- the geological storage characteristics and injection requirements including consideration of subsurface chemistry.
- the requirements to satisfy environmental and safety factors.

In the context of the above factors, it was a key project requirement that the specification must provide the project with the largest possible envelope acceptable to all parties in which to operate in a cost effective / economically viable manner.

3.4 Information gathering for the CO_2 specification development

It is acknowledged by CarbonNet that the project was starting with a good foundation, a solid base of knowledge from international reference projects and published FEED studies such as E.On Kingsnorth and Scottish Power Longannet as well as a number of other published documents on CO_2 specification development for point to point sources.

CarbonNet also had access to indicative CO_2 compositions of a range of local source proponents that had been developed at a pre-feasibility study level. These studies and output compositions proved a valuable input into the development of the CO_2 specification during the feasibility study.

The initial stage involved gathering information from a range of relevant sources as referenced in section 2.3, recognising available literature and published project reports to understand the status of research and developments in this area.

3.5 Consideration of whole of project constraints

Determining the appropriate CO_2 specification for the CarbonNet project went beyond simply determining the impact on the pipeline integrity of each gas component. Consideration had to be given to the whole of project (entire CCS chain) constraints, which included the requirements at the storage site, requirements for the safe design and operation of the pipeline (including the consideration of planned and unplanned releases) and the capabilities of, and impact to, the multiple source and capture projects. The controlling components across each element of the CCS chain were identified and are presented in Figure 3-2.

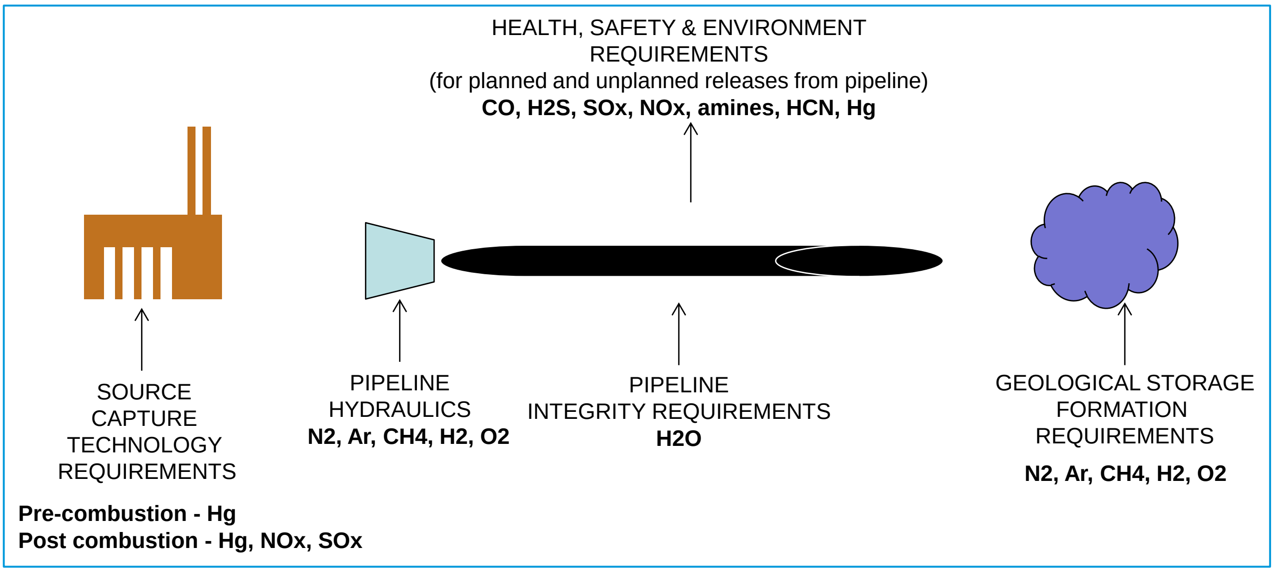

Figure 3-2 Controlling components across the CCS chain

The components that make up the CO_2 stream can generally be grouped based on their **primary** impact on pipeline design and operation as shown in Table 3.2 below.

Table 3.2 Primary impact by component

HEALTH AND SAFETY	PIPELINE INTEGRITY	ECONOMIC IMPACT
CO, H_2S, SO_x, NO_x, amines, HCN, Hg	H_2O	N_2, Ar, O_2, CH_4, H_2

Each component required consideration in terms of its impact on each of the key design considerations. The table presented in Figure 3-3 provides further detail of the typical issues associated with each component in CO_2 streams as presented in DNV's Recommended Practise for the Design and Operation of CO_2 pipelines DNV-RP-J202 [11].

Component	Properties									Comment
	Health & Safety	Pipeline capacity	Water solubility	Hydrate formation	Materials	Fatigue	Fracture	Corrosion	Operations	
CO_2	•	•	•	•	•	•	•	•	•	Non-flammable, colourless, no odour at low concentrations, low toxicity, vapour heavier than air
H_2O				•	•	•	•	•	•	Non-toxic
N_2		•	•							Non-toxic
O_2			•					•		Non-toxic
H_2S	•	(•)			•	•	(•)	•		Flammable, strong odour, extremely toxic at low concentrations
H_2		•	•				•			Flammable, non-condensable at pipeline operating condition
SO_2	•		•					•		Non-flammable, strong odour
CO	•		•							Non-flammable, toxic
CH_4+		•	•						•	Odourless, flammable
Amines	•									Potential occupational hazard
Glycol	(•)							(•)		Potential occupational hazard
Ref. Sec.	3.3.3	4.5.3	2.3.5	4.5.11	5	5.6	5.5	5.1	7	

Figure 3-3 Main issues related to various components in CO_2 streams [11]

Determining absolute limits on each component would be relatively simple if the CO_2 stream was a binary component mixture where interactions between components and the CCS system were well documented and understood. An example of the impact that binary mixtures of CO_2 and other components can have is given by the significant changes that the other components can have on the phase envelope. This in turn impacts on the pressure envelope within which the dense phase pipeline can operate, the supercritical fluid density, and the pipeline capacity and power required for pipeline operation and injection. The impact of various impurities on a pure CO_2 stream and how that relates to a change in the CO_2 phase diagram are illustrated in Figure 3-4.

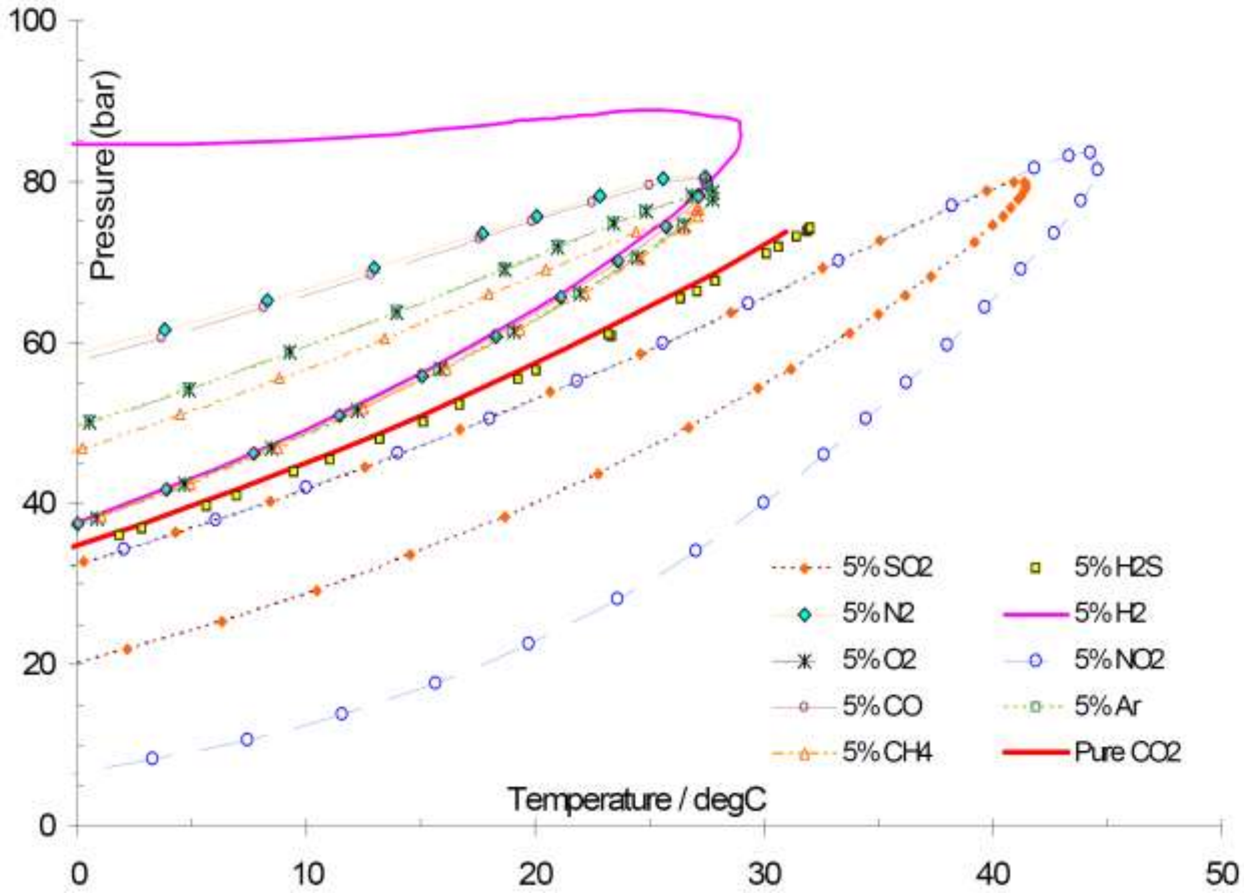

Figure 3-4 Phase diagram for CO_2 in binary combinations [12]

The impact of multiple components within the CO_2 stream and the combined effects of such components on the phase envelope remains an area of uncertainty. The components in the CO_2 stream which increase the toxicity will need to be considered and managed appropriately from a health, safety and environment perspective. The combined effects of components within the stream (e.g. the reaction between H_2S and SO_2) should be considered along with any impacts these components, or combination of components, have on the pipeline design requirements.

GERG 2008 or Refprop equations of state have been used, amongst other models, to provide predictions of CO_2 mixture properties for pipeline transport modelling. However it is understood there is a recognised weakness for CO_2 mixtures with some components using these models, most likely as a result of there being relatively limited data for those components. It is understood that future revisions to the models will address the model limitations once the research needed to provide the relevant data is complete.

3.5.1 Establish potential/representative source projects and compositions

CarbonNet consulted with a number of potential source proponents to understand the likely compositions of their CO_2 stream that would be transported into the CarbonNet Transport Network. Some of the potential CO_2 sources that were considered are presented in Table 3.3 along with their specific characteristics and implications for Victorian Lignite.

Table 3.3 Potential CO_2 Sources for the CarbonNet Project

CO_2 SOURCE	CHARACTERISTICS
Existing coal-fired power station with post-combustion capture	98 vol% CO_2 with many components below detectable level and presence of carryover of the selected capture solvent
New build IGCC	>98 vol% CO_2 with presence of CO, H_2S and other minor components
New build IGCC with integrated coal drying	>99.5 vol% CO_2 and other minor components
New build coal to products (CTX)	>98 vol% CO_2 with presence of H_2O and CO and other minor components
New build coal to fertiliser	~96 vol% CO_2 with presence of H_2 and H_2S and other minor components
Oxy-fuel plant	>91 vol% with presence of non-condensables N_2, Ar, O_2

As shown above the CO_2 stream composition ranges from 91-99.5 vol% CO_2 and consists of varying impurity types and levels as a result of the range of potential projects and technologies. With knowledge of the potential CO_2 source streams, PB used the approach outlined in Figure 3-5 to develop the specification.

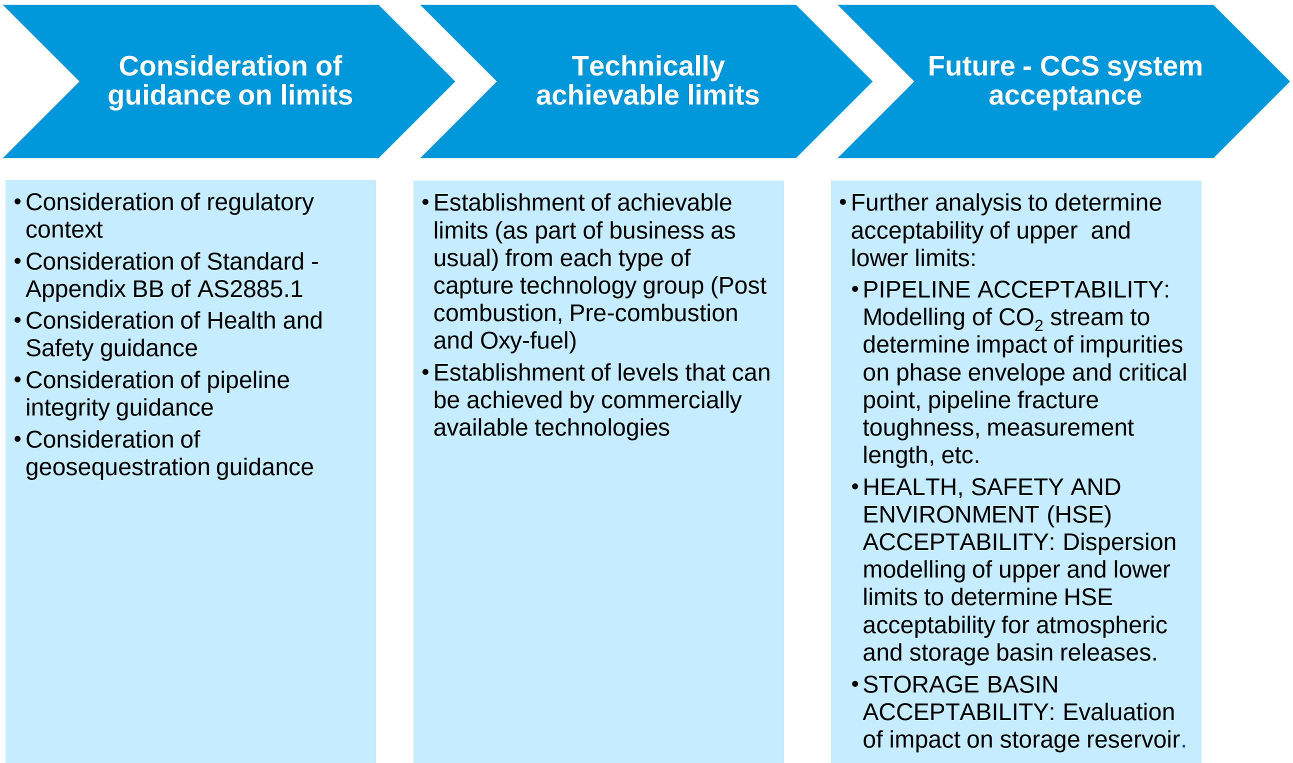

Figure 3-5 Summary of approach

Each of these is discussed in turn in the following section.

3.5.2 Consideration of guidance on limits

The regulatory context from the Greenhouse Gas Act and guidance from Appendix BB of AS2885.1 were first considered.

The other three key areas where guidance was sought included the health and safety aspects associated with planned and unplanned releases along the pipeline network, the requirements of the pipeline system and maintaining the integrity of the pipeline and finally the geological storage site requirements where the CO_2 would be permanently stored. Each of these are discussed below.

3.5.2.1 CONSIDERATION OF REGULATORY CONTEXT

In Victoria, geological sequestration of CO_2 is governed onshore by the *Greenhouse Gas Geological Sequestration Act 2008*, in state waters by the *Offshore Petroleum and Greenhouse Gas Storage Act 2010* and in commonwealth waters by the *Offshore Petroleum and Greenhouse Gas Storage Act 2006*. In each of these acts the greenhouse gas substance that is covered by the act can be carbon dioxide, another prescribed greenhouse gas, one or more incidental substances related to the carbon dioxide or prescribed greenhouse gas or a mixture, so long as the mixture consists overwhelmingly of carbon dioxide or another prescribed greenhouse gas. No waste can be added to the greenhouse gas stream.

The CO_2 specification therefore needs to adhere to these limitations, in particular to be 'overwhelmingly' carbon dioxide, or another prescribed greenhouse gas, that only 'incidental' greenhouse gas related substances are permitted to be with the stream and no waste is to be added to the stream.

3.5.2.2 CONSIDERATION OF APPENDIX BB OF AS2885.1

Appendix BB of AS2885.1 [1] (Guidelines for pipelines for the Transport of CO_2) suggests a preliminary approach to consideration of stream composition and its impacts on measurement length. In broad terms this approach is workable, but the specific stream composition in question requires careful consideration, and there may be few precedents for understanding the hazard level of the stream being analysed.

In AS2885 "Measurement length" refers to the distance from the pipeline at which the thermal radiation from combustion of gases escaping a rupture in the pipeline would result in 4.7 kW/m^2 radiation intensity. It is calculated on the basis of a quasi-steady state release with the discharge rate fixed at the rate calculated 30 seconds after a full bore rupture. A thermal radiation level of 4.7 kW/m^2 will cause injury (at least second degree burns) after 30 seconds exposure.

Under the AS2885.1, the pipeline route is allocated location classes that reflect threats to pipeline integrity, and risks to people, property and the environment. Location classes are assigned based on the most demanding land use within the measurement length. Based on the most demanding location class within the measurement length, design requirements will vary to manage the risks to acceptable levels.

Appendix BB of AS2885.1, section BB4.2 notes that "*Until further research on dispersion of CO_2 releases is completed, the measurement length for definition of the location class limits may be estimated on the basis that the pipeline is transporting methane (see Clause 4.3.2 and Appendix Y); however, the measurement length should be extended locally wherever the landform suggests that spread of the gas cloud in a particular direction may be promoted by gravity drainage.*" [1] When the relative harm associated with thermal radiation from combustion of a natural gas pipeline rupture versus CO_2 plume dispersion are considered, this approach is considered conservative.

Appendix BB of AS2885.1 (Pipelines - gas and liquid petroleum) states: "…*it is possible that the danger from a cloud of released gas may be governed by the H_2S concentration rather than the CO_2 concentration. The effects of H_2S become dominant if the proportion of H_2S in the transported gas exceeds about 0.2 % [2000 ppm]*...".[1] Whilst H_2S is explicitly identified the same is true of other potential trace components.

Appendix BB does not preclude the use of a more onerous measurement length if the composition of the pipeline is more hazardous. Depending on the local circumstances the more onerous measurement length might result in certain sections of the pipeline being uprated to a location class requiring higher cost design solutions.

Subsequent to the CO_2 specification development, CarbonNet commissioned a report on Dispersion modelling techniques for CO_2 pipelines in Australia [9]. The report reviews the application of AS2885.1 for CO_2 pipelines as well as a review of the available dispersion models that can be used in designing a CO_2 pipeline system. The report found that use of the measurement length based on the pipeline transporting methane, as per the recommendations of Appendix BB, is appropriate in the preliminary design stage. In the detailed design stage consequence analysis is required to identify the appropriate measurement length. During the detailed design stage it will be important to identify the maximum impurity concentrations so that dispersion modelling can provide appropriate risk analysis results especially where the threshold levels of harm may not be set by CO_2.

Whilst these studies were being undertaken, the EP CRC was about to embark on an exercise looking at dispersion modelling of CO_2 + H_2S. Understanding continues to evolve regarding CO_2 streams containing varied impurities, but as a principal designers should be conservative in view of present uncertainties.

3.5.2.3 CONSIDERATION OF HEALTH AND SAFETY GUIDANCE

Transporting large volumes of CO_2 via pipeline has the potential to impact on nearby receptors in the event of planned or unplanned releases of the process fluid from the pipeline. Some of the components with potential to be present in the CO_2 stream (e.g. CO, H_2S, SO_2) are significantly more toxic than CO_2. Therefore all components of the stream (including CO_2) need to be considered when assessing the level of risk and the associated pipeline design requirements.

Guidance was provided as to the management of Health and Safety related risks associated with the pipeline network, most notably, risk management in the areas of planned and unplanned releases of pipeline gas. Specific guidance related to the pipeline component limits from a health and safety perspective aimed for risk avoidance through mitigation and management. The guidance outlined that the desirable starting point was to be based on the Australian Occupational Health & Safety Short Term Exposure Limits (STEL's) and investigations should be conducted to evaluate the technical and financial practicalities of achieving these levels. The Australian STEL limits for components of interest are provided in Table 3.4 below.

This is a very conservative approach equivalent to assuming that the sensitive receptor is **inside the pipeline** (except that the CO_2 concentration at this point would be indicatively 33 times the CO_2 STEL). It is also noted that the Australian STEL levels are generally seen to be far lower than what can be achieved by commercially available purification equipment. Therefore if all components within the CO_2 stream were to comply with the Australian STEL, significant additional purification equipment would be required at each source project, adding substantial costs to each source project, in order to meet such tight limits - and by definition CO_2 would always be a large multiple of the STEL.

The Dynamis CO_2 Quality Recommendations report was also considered and the manner in which it addressed safety and toxicity limits amongst other items. Their approach to trace component limits from a health and safety perspective also made use of STEL limits as reference values, but based on a ratio of the STEL in an attempt to ensure the individual component levels were not more critical than the CO_2. Essentially their approach was to:

- Define that CO_2 should be the most "critical" component of the stream.
- Compare the STEL of a range of potential trace components to the STEL of CO_2 (i.e. a STEL ratio).
- For a trace component to be no more critical than CO_2, its concentration would need to be no greater than the CO_2 concentration multiplied by the above STEL ratio. For example, if a trace component had a STEL of 1 % of the CO_2 STEL, then the equivalent concentration at which it would be equally critical to CO_2 would be ~1 %.
- Introduce a safety factor of 5 for each trace component concentration limit calculated based on the above, to further bias in favour of CO_2 being the most "critical" component of the stream.

Based on the Dynamis approach the limits based on the Australian STEL are presented in Table 3.4.

Table 3.4 Health and safety limits for trace components based on Dynamis approach

COMPONENT	AUSTRALIAN STEL [PPMV]	DYNAMIS APPROACH - LIMITS BASED ON AUSTRALIAN STEL [PPMV]	DYNAMIS LIMITS
CO_2	30000	-	
H_2S	15	100	200
CO	200	1,333	2000
SO_2	5	33	100
NO_2	5	33	100
Amines (MEA)	6	40	-
HCN	4.7	31	-
Hg	0.003	0	-
HF	3	20	-
HCL	5	33	-
C_2H_4O (Acetaldehyde)	50	333	-
Ethylene glycol (vapour)	40	267	-
Ethylene glycol dinitrate	0.05	0.33	-

If CarbonNet was to adopt the Dynamis approach to establish the minor component limits, the low Australian STEL's result in lower limits than those reported by Dynamis and various questions therefore remain;

- → Are the technically achievable limits at the source projects for the range of capture technologies sufficient to achieve the limits using this approach? (Refer to section 3.7 for further details).
- → What impact may diffusion, synergy effects or potential additive effects that may arise from the various impurities have on the relative exposure levels? Therefore is a safety factor of 5 too onerous, or not onerous enough?
- → Does CO_2 have to be the most critical component in the pipeline? And what are the implications for the pipeline design if other components are more critical?

CarbonNet chose to adopt a risk based approach, to review the entire CCS chain and the impacts of the components and so that at the feasibility stage, the CO_2 specification has greater levels of impurities than the Australian STEL and greater levels than applying the Dynamis approach. The impact that this may have on the design requirements of the pipeline to ensure it meets the required standards from a health and safety perspective will need to be further evaluated as the project progresses.

3.5.2.4 CONSIDERATION OF PIPELINE INTEGRITY

Water is the primary consideration for pipeline integrity. It is acknowledged and widely accepted that free water combined with CO_2 is very acidic. The wet CO_2 is very corrosive and therefore poses a threat to carbon steel pipeline system integrity. Since carbon steel is commonly used for most pipelines due to economic considerations (See section 3.8.1), the maximum water content should not exceed the saturation level or solubility limit, i.e. no free water present. The solubility limit is dependent on the operating pressure, temperature and composition of the stream. (Refer to Figure 3-6 below).

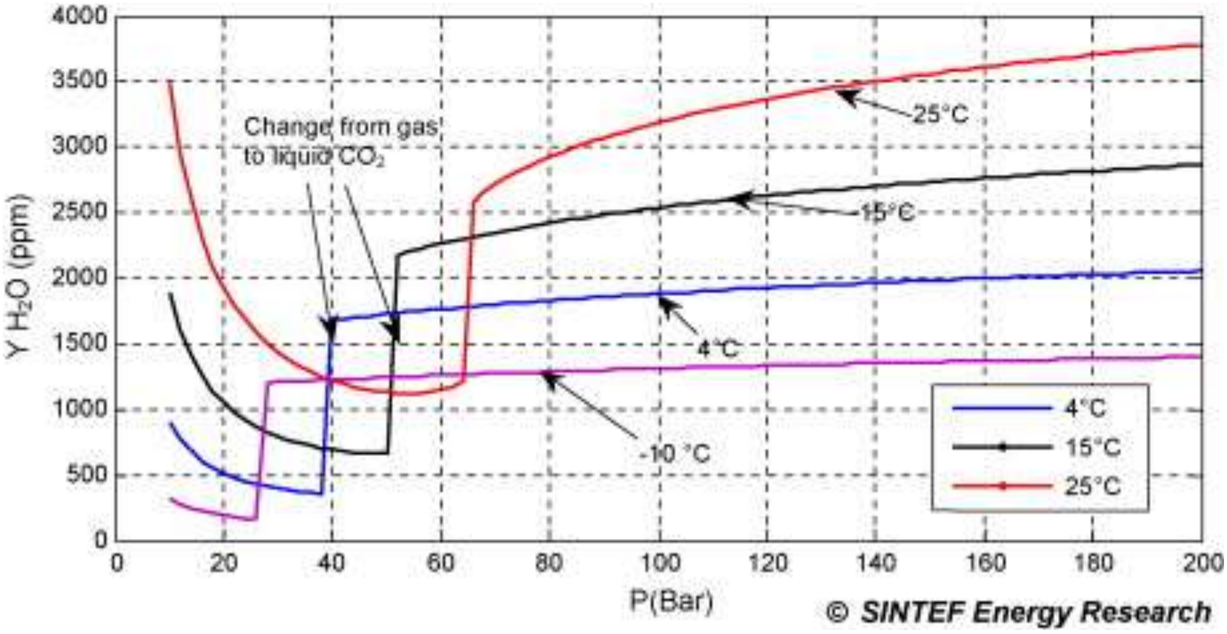

Figure 3-6 Solubility of water in CO_2 [13]

A variety of water concentration limits have been published for various projects globally and range from 20 ppmv to 650 ppmv [14]. The limit depends mostly on the amount of sulphur and other impurities in the stream. Lower moisture range is typically set for higher sulphur content and the higher range for lower sulphur content.

Due to the risks associated with corrosion and hydrate formation in the pipeline the water content should be controlled at a safe margin below the saturation point of the pipeline operating conditions including the conditions that will be present at start-up and during depressurisation events. The main driver is to ensure no free water will be present in the pipeline at any time. Since the system design life for the pipeline network is 40 years, a lower specification will minimise the opportunity for internal corrosion and damage in the pipeline throughout its extended operating life.

3.5.2.5 CONSIDERATION OF GEOSEQUESTRATION REQUIREMENTS

The geological storage of CO_2 has its own set of requirements driving the purity level of CO_2 and the level of impurities within the CO_2 stream. During the feasibility study the CarbonNet's Geoscience Exploration and Development team advised that the contaminants should be limited to less than 2 vol% total which was based on the following rationale:

- Loss of reservoir capacity due to lower compressibility of non-condensables and changes to CO_2 solubility due to condensables (SO_2)
- Potential mineral depositions as a result of reactions between condensable components (NOx, SOx)
- As research continues in the subsurface it may be that storage may impose more stringent conditions or more relaxed conditions than those currently specified and the CO_2 specification would need to be revisited and reconsidered in light of enhanced knowledge.

It should be noted here that the proposed CO_2 specification tolerates an increased level of impurities than the guidance recommended. It is acknowledged that this may have an impact on storage capacity and additional work is required to confirm the acceptability of the higher level of impurities on the subsurface.

3.6 CO_2 specification rationale by component

Each component was considered in turn, in order of their assumed importance. The objective was to define an upper and lower limit for each component within the CO_2 stream to provide an envelope specification to allow source proponents to test the commercial implications of conforming to the lower or upper limit. Systematically each component was analysed with consideration of the following:

- Primary drivers – whether it was a technical, pipeline, HSE, or storage limitation
- Any key requirements, limitations or effects of other impurities
- Available literature
- Project precedence - Typical specifications from representative projects
- Limits achieved by pre-combustion, post-combustion, oxy-fuel technologies as part of BAU (to determine the upper limit)
- Limits achievable by the addition of commercially available technology beyond BAU (to determine the lower limit)
- Order of magnitude estimates for achieving limits beyond BAU
- Implications of proposed limits (identifying any key benefits and disadvantages).

The above approach resulted in a CO_2 specification with an upper and lower limit for most components. In most cases the upper limit represented roughly the levels achieved as part of business as usual by the source projects, while the lower limit (tighter limit) represented the level achieved with the addition of commercially available technology to remove or reduce the presence of the respective constituent from the stream.

When considering each component in turn it was recognised that the moisture limit was a vital component due to the following known limitations:

- Corrosion effects from water reacting with CO_2, SO_2 or H_2S to form carbonic acid/ and or sulphuric acid.
- Hydrate formation with CO_2, CH_4 and H_2S.
- Impurities such as CH_4 and possibly H_2S, O_2 and N_2 lower the solubility limit of water.

As a result, establishment of the moisture limit was considered a priority in the development of the CO_2 specification and was considered first before all of the other components. Refer to section 3.7.1.

3.7 Technically achievable limits – Business as usual

In order to minimise the whole of project costs high level techno-economic trade off assessments were conducted. This involved evaluating the *technically achievable* limits for the range of carbon capture technology groups. These technology groups included Oxy-fuel, Post Combustion Capture (PCC) and Pre-combustion Capture technologies. The range of technologies within each group are likely to produce similar CO_2 purity levels, as part of their Business As Usual[5] (BAU) process. However the presence of impurities/trace components will vary between the technology groups due to the type of feed stock and the specific solvent or other separation technology utilised.

The approach to determining the Technically Achievable Limits included:

1. Evaluation of the BAU product qualities of each technology group without additional purification technologies to determine the upper limit.
2. Evaluation of the technically achievable lower limit of each technology group based on the removal of efficiencies of commercial / near commercially available[6] purification technologies.

The likely business as usual outcome across the three capture technologies for each of the main components in the CO_2 stream are summarised in Table 1.6 below.

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[5] Where BAU is considered as the process design or operating conditions that would occur as normal practice by the source when there are no limitations being imposed by the pipeline specification.
[6] The term “commercially available” is not entirely correct as many purification technologies, particularly for Oxy-fuel, have not yet been commercialised on Oxy-fuel flue gas streams. In this context those technologies that are the closest to commercialisation have been considered.

Green shading in the table represents that the lower limits of the CO_2 specification (as presented in Table 3.5) can be achieved as part of BAU, with no additional treatment or purification required. Orange shading represents levels achieved as part of BAU that then can be reduced further with the addition of commercially available technologies.

Table 3.5 Business as usual – Component limits

COMPONENTS	POST-COMBUSTION	PRE-COMBUSTION	OXY-FIRED
CO_2	>98 vol%	>98 vol%	>85 vol%
H_2O	Leading capture technologies, e.g.: Fluor, MHI PCC show produced CO_2 streams containing high moisture levels (up to 5wt%) before compression. After compression moisture levels are likely to be less than 2200 ppmv. Further drying is required for these PCC technologies.	The moisture content from pre-combustion technologies can reach below 100ppmv without the use of a drying plant, depending on the solvent used.	Coal based oxy-firing typically produces very high moisture (up to 20wt% moisture) levels in the flue gas stream from combustion of moisture in coal.
SO_2	Post combustion capture technologies require low SO_2 levels of <10ppmv to reduce amine based solvent losses. Achieving low levels of SO_2 is common practice (i.e. STEL type levels).	The reducing environment of a gasifier result in low SO_2 levels as part of business as usual.	Almost all sulphur from coal feedstock is converted into SO_2 in the combustion process. Sulphur concentrations for Latrobe Valley coals are commonly 0.4% Sulphur (by mass). This implies an unabated SOx level of up to 2,000ppmv in the CO_2 flue gas.
NOx	PCC solvents are sensitive to NOx impurities in flue gas. The tolerance levels for various solvents are generally recommended to be below 100ppmv. Product NOx levels for PCC plants therefore tend to be very low.	During gasification, most of the coal bound nitrogen is converted to nitrogen gas. BAU is therefore virtually zero NOx.	Oxy-fired plants have been seen to contain higher NOx concentrations than air blown boilers due to higher combustion temperatures and a more concentrated flue gas stream.
H_2S	Produce virtually H_2S free CO_2 streams.	BAU is to recover H_2S as a separate stream in the AGR Unit. These are commonly Selexol (solvent mixture of dimethyl ethers of polyethylene glycol) process or similar Rectisol process (methanol wash).[7]	Produce virtually H_2S free CO_2 streams.

[7] The feasibility study assumed BAU as using physical solvents where H_2S and CO_2 would be produced in separate streams, however certain applications may favour the use of chemical solvents with H_2S and CO_2 produced in a single stream. The implications of higher H_2S levels generated under these conditions and the cost to further treat the CO_2 to remove/oxidise the H_2S compared to the implications associated with relaxing the H_2S limit should be assessed during FEED.

COMPONENTS	POST-COMBUSTION	PRE-COMBUSTION	OXY-FIRED
CO	CO levels in flue gas are minimised as part of business as usual.	Syngas formed from the gasification process contains largely Hydrogen and Carbon Monoxide. During the AGR process, the solvent selectively removes H_2S and CO_2 from the syngas stream. AGR solvents have a mild selectivity for CO, therefore trace quantities of CO are carried over into the CO_2 product stream. IGCC plants designed for high CO_2 capture rates and gasification for hydrogen production will utilise water gas shift reactions to reduce the CO content and therefore only low levels of CO will be carried into the CO_2 stream.	CO levels in flue gas are minimised as part of business as usual.
Hg	Removed as part of the process to below detectable limits in order to protect downstream equipment.	Removed as part of the process to below detectable limits in order to protect downstream equipment.	Requires the installation of mercury control equipment
Non-condensables	Low levels (2-3vol%) of these components could be expected as part of business as usual.	Low levels (<2-3vol%) of these components could be expected as part of business as usual.	Contains large amounts of Ar, N_2 and O_2 non-condensables.

For each orange shaded box, an order of magnitude cost was developed for the commercially available technology required to reduce each respective component. Based on all available data, the following key outcomes for each component were recommended.

3.7.1 Moisture

The primary driver for specifying a limit on moisture is based on maintaining pipeline integrity.

Based on the achievable drying levels as shown in Figure 3-7, and due to the risks associated with corrosion and hydrate formation in the pipeline the proposed limit for moisture was set at 100 ppmv.

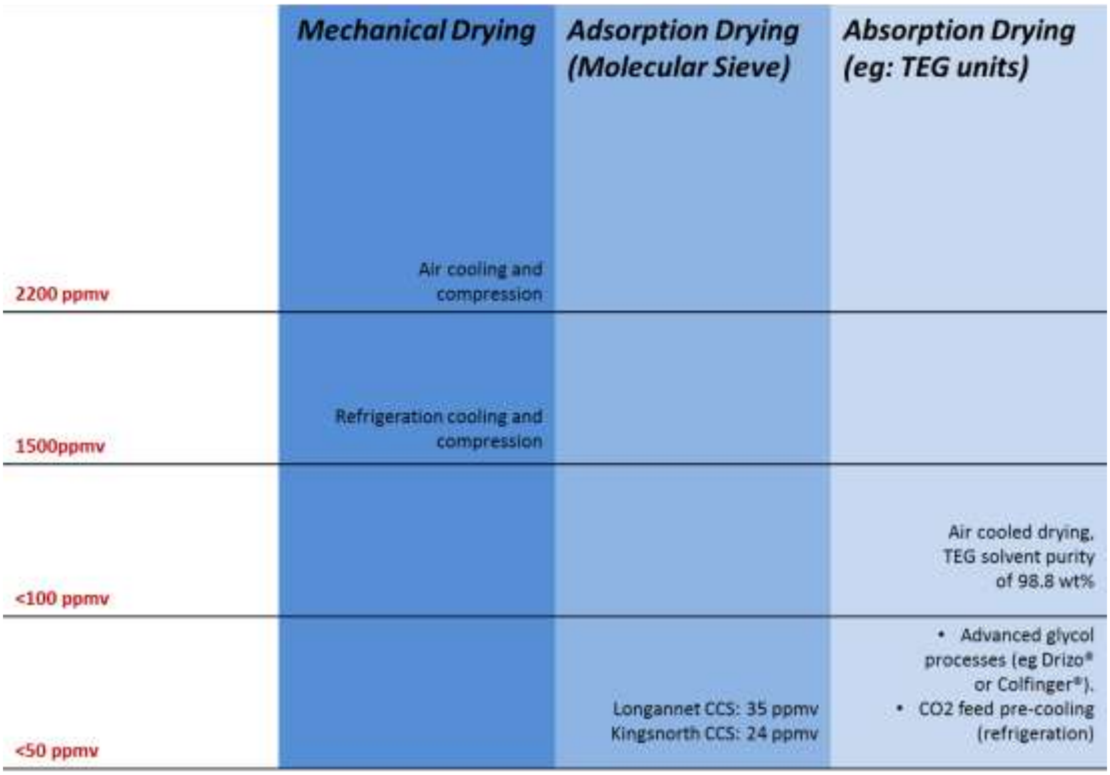

Figure 3-7 Achievable drying levels[8]

The reasoning for the proposed limit is as follows:

- Chemical drying processes are required to achieve 500 ppmv as this is well beyond the capability of a mechanical drying process.
- As is presented in literature (i.e. the Dynamis CO_2 quality recommendations report), a limit of 500 ppmv provides a good safety margin in preventing free water formation in the pipeline and protects pipeline integrity for carbon steel pipes.
- The marginal capital and operating costs to reduce the moisture limit from 500 ppmv down to 100 ppmv have been found to be not significant.
- To dry beyond 100 ppmv advanced processes and / or refrigeration cycles are required to improve the drying efficiency (notably with TEG systems).

3.7.2 Sulphur dioxide (SO_2)

The primary driver for specifying a limit on sulphur dioxide is based on health, safety and environment implications. The presence of SO_2 in the CO_2 stream lowers the solubility limit of water and there are potential corrosion effects from water reacting to form sulphuric acid. Consideration to the economically practical limits achievable are a secondary consideration.

Pre-combustion and post-combustion technologies generally result in low levels of SO_2 as part of business as usual, while a typical oxy-fuel plant if deployed in the region could result in levels of ~2000 ppmv without additional treatment.

An upper limit of 2000 ppmv was proposed as it can be achieved by all capture technologies as part of BAU without additional treatment.

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[8] Liquid TEG desiccant systems can achieve levels of ~150 ppmv moisture. To reduce moisture levels beyond that enhanced TEG processes are required and can achieve levels of ~30 ppmv.

A tight moisture limit will allow for a more relaxed SO_2 limit as the risk of acid forming corrosive species is minimised. However it is unknown at this stage whether the moisture limit of ~100 ppmv with a more relaxed limit of 2000 ppmv is sufficient to reduce the risk of acid forming corrosive species. This would need to be determined during FEED.

The upper limit of 2000 ppmv would permit an oxy-fired plant to supply to the network, however the impacts of this on the phase envelope and critical point of the stream need to be determined, which could subsequently impact the fracture control, wall thickness, measurement length etc. It is anticipated that a blended pipeline spec of 670 ppmv could be obtained for no additional capital cost if one oxy-fired source project stream of 1 Mtpa is blended with two other non oxy-fired streams, which are free of / contain ultra-low levels of SOx.

A lower limit of 200 ppmv was proposed. Note that the Australian STEL for SO_2 is 5 ppmv and based on the Dynamis approach the limit would be 33 ppmv. The capital and operating costs will increase significantly for oxyfuel based source projects if they are to achieve ultra-low SO_2 limits (i.e. in the order of STEL type limits such as a 5 ppmv for SO_2). In comparison the potential required investment can be reduced by two-thirds if the SO_2 limit is set at 200 ppmv rather than 5 ppmv. As a result the lower limit of 200 ppmv was proposed.

In summary, an oxyfuel project feeding into the network will result in the higher limits of SO_2 in the CO_2 stream. Although the limits specified are higher than health and safety guidance levels, during the next phase (FEED), further analysis or dispersion modelling should be undertaken to understand the implications of the proposed limits from a health, safety and environment perspective during planned (venting) or unplanned (emergency) release events. If oxy-fuel technology is not a prospective source then the focus should be on the implications of the lower limit of 200 ppmv.

3.7.3 Nitrogen oxide (NOx)

The primary driver for specifying a limit on nitrogen oxide is based on the health, safety and environment implications. The presence of NOx in combination with free water will form acids (nitric acid) which will have a significant effect on the corrosion rate, potentially impact on pipeline integrity and safety. Consideration to the economically practical limits achievable are a secondary consideration.

Pre-combustion technologies generally result in low levels of NOx as part of business as usual. Post-combustion capture technologies require low NO_2 levels of <100 ppmv due to solvent tolerance levels. While a typical oxy-fuel plant will result in high NOx levels (~2500 ppmv) without additional treatment.

An upper limit of 2000 ppmv was proposed as it can be achieved by all capture technologies as part of BAU without additional treatment. Only the Oxy-fuel technology group would be required to install technology to remove NOx to achieve the Lower Limit specified. Although de-NOx technology has not been commercially proven on Oxy-fired streams, it is anticipated that a 90 % reduction efficiency may be achieved based on performance with conventional flue gas.

A lower limit of 250 ppmv was proposed. Note that the Australian STEL for NOx is 5 ppmv and based on the Dynamis approach the limit would be 33 ppmv. The capital and operating costs will increase significantly for oxyfuel based source projects if they are to achieve ultra-low NOx limits (i.e. in the order of STEL type limits such as a 5 ppmv for NOx).

In summary, an oxyfuel project feeding into the network will result in the presence of higher limits of NOx in the CO_2 stream. Although the limits specified are higher than health and safety guidance levels, during the next phase (FEED), further analysis or dispersion modelling should be undertaken to understand the implications of the proposed limits from a health, safety and environment perspective during planned (venting) or unplanned (emergency) release events. If oxy-fuel technology is not a prospective source then the focus should be on the implications of the lower limit of 250 ppmv.

3.7.4 Hydrogen sulphide (H_2S)

The primary driver for specifying a limit on H_2S is based on health, safety and environment implications. In addition, H_2S in the presence of free water may potentially lead to corrosion assisted fatigue. The proposed limit for H_2S is 100 ppmv as it can be achieved by all capture technologies as part of BAU without requiring additional treatment.

The Australian STEL for H_2S is 15 ppmv and based on the Dynamis approach the limit would be 100 ppmv. The capital and operating costs will increase significantly for pre-combustion based source projects if they are to achieve ultra-low H_2S limits (i.e. in the order of STEL type limits such as a 15 ppmv for H_2S).

Although the proposed H_2S limit specified is higher than health and safety guidance (STEL) levels, during the next phase (FEED), further analysis or dispersion modelling should be undertaken to understand the implications of the proposed limits from a health, safety and environment perspective during planned (venting) or unplanned (emergency) release events.

3.7.5 Carbon monoxide (CO)

The primary driver for establishing the CO limit is health, safety and environment as CO is toxic, and hence there is concern with releases into the atmosphere. However in contrast to other toxic contaminants, CO (28 g/mol) is lighter than CO_2 (44 g/mol) and air (29 g/mol) and therefore would not tend to settle or accumulate at ground level in the same manner as other contaminants. In the presence of water it has the risk of forming a corrosive acid, however the limit can be relaxed based on the tighter moisture limit specified (~100 ppmv).

An upper limit of 5000 ppmv was proposed as it can be achieved by all capture technologies as part of BAU without requiring additional treatment.

While the Australian STEL for CO is 200 ppmv, a lower limit of 900 ppmv was proposed. Pre-combustion technology, using a physical solvent with a single stage of water gas-shift, is likely to require CO removal/oxidation technology applied to the CO_2 stream to achieve this lower limit. As conventional CO removal technology from flue gas streams is potentially unsuitable, further review of the limitations of other commercially available CO removal technologies should be considered for such source projects during FEED. Further analysis or dispersion modelling should be undertaken to understand the implications of the proposed CO limits from a health, safety and environment perspective during planned (venting) or unplanned (emergency) release events.

3.7.6 Mercury (Hg)

The primary driver for establishing the limit on Hg is health, safety and environment. The proposed limit for mercury was Below Detectable Level. Both pre-combustion and post-combustion technologies remove Hg as part of their process to below detectable limits in order to protect downstream equipment. Only oxy-fired technologies would be required to install additional mercury removal equipment. A range of mercury removal technologies are readily available at a relatively low cost.

3.7.7 Minor Components

Minor components may exist in the CO_2 product stream at a trace level which could be as a result of carryover from combustion based chemicals or a carryover of chemicals used in the capture process. These components could include HCN, HCl, HF, C2H4O (Acetaldehyde), amines (MEA), NH4 etc.

Instead of reviewing all possible minor components and setting absolute limits on each of them, a more reasonable approach of "review by materiality" was preferred. A reasonable materiality threshold should be set, components falling below which are automatically deemed acceptable.
Those above the materiality threshold should be subject to dispersion modelling to determine Health and Safety acceptability for planned and unplanned releases.

It was proposed that the materiality threshold is the Australian STEL values for each component. It is highly likely that most minor components will fall below this threshold. The thresholds are presented in Table 3.6.

Table 3.6 Minor components

MINOR COMPONENT	STEL [PPMV][9]
Amines (MEA)	6
HCN	4.7
Hg	0.003
HF	3*
HCL	5*
C2H4O (Acetaldehyde)	50
Ethylene glycol (vapour)	40
Ethylene glycol dinitrate	0.05*

*STEL values unavailable. Time Weighted Averages (TWA) are proposed as a basis for materiality in the absence of STEL data.

3.7.8 Other hydrocarbons

A single limit of 0.5 vol% was proposed for the sum of all “Other Hydrocarbons”. This limit is typically achievable without the need for additional purification equipment.

3.7.9 Non-condensables

The primary driver for specifying limits on non-condensables is transport and sequestration efficiency, i.e. non-condensables should be minimised to avoid the additional pipeline compression costs to transport as well as the additional pore space taken up in the storage basin.

An upper limit of 5 vol% and a lower limit of 2 vol% was proposed. From a health, safety and environment perspective the proposed limits are not seen to represent a risk. The proposed limits on non-condensables is most likely to impact only oxy-fuel streams.

The quantity of non-condensables in the CO_2 is largely dependent on the purity of the oxygen from the air separation plant and the amount of air ingress into the boiler. The non-condensable levels can be further reduced through the application of a cold box. Both the upper and lower limit proposed require roughly equal capital investments for cold box equipment to cryogenically remove the non-condensables. Although very little information is available on the capital costs for the application of cold box technology on oxy-fuel plant, they are expected to be relatively high compared to other purification equipment costs. These capital costs have the opportunity to be avoided either through stream blending or incorporation of a tariff structure to account for lost pore space and extra transportation energy costs. The CarbonNet’s tariff structure could in practice mean that each proponent will have their own system usage fees – lower fees for users delivering pure CO_2 into the network, and higher charges for users delivering lower purity, low density CO_2 into the network. Refer to section 3.8.3.

Such an approach, based on flexibility of CO_2 specification within the bounds of some real, overriding constraints, would allow for equitable application of system usage charges amongst all proponents, and would provide a means for maximising the ability of the system to accept future unknown CO_2 specifications from technology applications which may not be forecast at present.

[9] “Guidance on the Interpretation of Workplace Standards for Airborne Contaminants”, Safe Work Australia

3.8 Trade-off studies

A number of trade-off studies were carried out to help inform the feasibility design and define the CO_2 specification limits.

3.8.1 Water content versus pipeline material study

In the pre-feasibility study the assumption was made that the most suitable pipeline material for the network would be carbon steel (CS), in line with a moisture limit of 100 ppmv for CO_2 streams entering the network. In this stage (feasibility study) this original assumption was verified by considering the use of a corrosion resistant material for the pipeline and associated ancillary equipment, along with a relaxed moisture limit to reduce or avoid capital and operating costs associated with dehydration equipment at the source capture projects. *Note the purpose of this study was not to verify the moisture limit but to compare the installation of dehydration equipment with installation of higher grade steel pipelines.*

A Net present cost (NPC) comparison was undertaken for the base case (carbon steel pipeline network) versus the use of a corrosion resistant material for the pipeline and associated equipment, along with a relaxed moisture limit to reduce or avoid capital and operating costs associated with dehydration equipment at the source and capture projects.

The results indicated that for the CarbonNet Foundation Network, a CS pipeline with dedicated TEG dehydration units installed at each source project (up to 5 projects), has a lower NPC than installing a transport network in 316L SS lined CS pipeline. The NPC differential decreases as the number of source projects increases and will break even as the number of source projects exceeds six. However, the potential impact on reduced compressor material costs and injection well material requirements were not included in the analysis, which further supports the recommendation for dedicated dehydration units at each source.

3.8.2 Pipeline operating phase - supercritical versus gas phase

The most efficient way to transport CO_2 is in a supercritical phase, as for a given pipe diameter it allows for substantially higher throughput than transporting at a lower pressure gas phase. CO_2 in the supercritical state has the density of a liquid and the viscosity of a gas.

In the pre-feasibility study the assumption was made that CO_2 would be transported in dense phase i.e. supercritical or possibly liquid rather than gaseous phase. During the feasibility study this original assumption was tested.

It is noted that two international CCS projects contemplated operating their pipelines in gas phase, particularly in the early stages; E.On Kingsnorth and Scottish Power Longannet. It is noted that there may be others.

E.On's Kingsnorth project pipeline was designed to transport CO_2 in the gaseous phase in the early years and dense phase in later years. Besides reported benefits such as operational flexibility, similar overall project costs, reduced design complexity and possible future expansion options, for their project, the approach was driven by the low reservoir pressures during the initial injection years, (i.e. the reservoir pressure will be as low as 3 bara).

Scottish Power's Longannet project was proposing to use existing onshore gas pipeline infrastructure, and therefore decided to operate in gaseous phase due to the design pressure limitations of the existing pipelines. The CO_2 was compressed to dense phase at St Fergus for transportation offshore.

Since operating in gaseous phase was contemplated and selected by other CCS projects, an analysis on operating in supercritical phase versus gaseous phase for transportation by pipeline for the CarbonNet project was also explored.

The operating phase study considered three different scenarios for the CarbonNet transport network: dense phase (16.5 MPa inlet pressure, 20 MPa design pressure), gas phase (5 MPa inlet pressure, 7 MPa design pressure) and gas phase for future dense phase operation. The study sought to identify (at a concept level) a close-to-optimal design concept for the transport of 5 Mtpa for each scenario in terms of pipeline diameter and frequency of intermediate compressor stations. The net present cost of the optimised solutions were compared, taking into account pipeline and compressor station capital costs, compressor station power consumption and other operating costs. The findings of this study were as follows:

The gas phase pipeline concept was a 750 mm diameter pipeline with no intermediate compressor stations, but with a compressor station required at the injection point to deliver CO_2 at appropriate conditions to meet wellhead and reservoir pressure requirements. The dense phase pipeline concept was a 400 mm diameter pipeline with no intermediate compressor stations, and no compression required at the wellhead. Based on the selected pipe sizes, overall a gas phase pipeline results in slightly reduced overall compression energy (< 3 %) required for the network compared to a supercritical phase pipeline. It is also acknowledged that there may be potential regulatory/approvals, community consultation and risk consideration benefits gained from an initial gas phase design.

From a commercial viewpoint, there are substantial cost savings by operating in dense phase for the CarbonNet foundation network. The NPC for a pipeline designed to operate in dense phase is in the order of 10 % less than a pipeline designed to operate in gas phase.

E.On's Kingsnorth and Scottish Power's decision to operate initially in gaseous phase was driven by the low reservoir pressures and the use of existing assets (natural gas pipeline) respectively. This is not applicable or appropriate to the CarbonNet project due to higher injection pressures required at the storage site (e.g. ~11 MPa) and the fact that CarbonNet will be installing a new pipeline to transport CO_2.

The outcome of this study was useful to confirm the merits of operating the pipeline above supercritical pressures, the basis of which fed into the development of the CO_2 specification.

3.8.3 Preliminary commercial considerations (tariff versus purity)

A theoretical concept-level example of how pipeline tariffs might vary for a pure versus impure CO_2 stream was considered. The actual tariff structure will depend heavily on the commercial structure ultimately selected for CarbonNet, along with the expectations of how and when costs will be recovered from commercial users of the network. A concept level study assessed the different cost per tonne of CO_2 required for the different fractions of pipeline and storage capacity that occurs between pure CO_2 and lower purity CO_2 sources. The study indicated that (as expected) low purity CO_2 should rightly incur higher CCS network usage tariffs, but not significantly higher to be prohibitive for those sources. In normal operation the low purity source would also experience slightly higher operating costs for their compression plant, as an incrementally higher delivery pressure into the network would be required.

Allowing a variable tariff approach in a transport network should allow for new CO_2 sources to make their own economic assessment of CO_2 purification requirements.

3.9 Risk workshops

The CO_2 specification was a key component of the basis of design that was used to conduct the HAZID risk workshop. The HAZID was a process that was used to identify and analyse significant hazards based on reference to process design documents which included the Basis of Design, the operating philosophy and PFD's.

A whole of project risk workshop was also conducted by the design team which considered the CO_2 specification. Risks were recorded and rated utilising the common definitions of probability, consequence, and overall severity. Additional risk assessments were subsequently conducted as required to provide a particular technical focus. The risk workshop identified the need for dispersion impact assessment and measurement length investigations to indicate areas of higher risk that may require a different location class.

Appendix BB of AS 2885 requires that a detailed investigation of the dispersion effects of CO_2 stream be undertaken. This is most appropriately undertaken in the FEED and detailed design stages of the project. However, prior to this detailed analysis an empirical assessment of the likely dispersion behaviour was undertaken during the feasibility stage of the project.

3.10 Peer review & Independent verification and review

The CO_2 specification was peer reviewed by Phil Venton (Energy Pipelines CRC contributor and Gas Pipelines Standards Committee member) and Dominic Cook (CCS Manager, PB UK)

An Independent Verification panel also provided a robust due diligence assessment of the deliverables prepared under the Transport feasibility study which included review of the CO_2 specification as part of the basis of design. The verification panel consisted of local and international CCS specialists from GHD, CCS TLM and Peter Tuft (PT&A Pty Ltd).

3.11 Consultation with source proponents

The CO_2 specification was distributed to all of the source proponents to seek feedback on the proposed limits set and determine the flexibility, suitability and applicability of the approach taken. There were some instances where the source proponents' specification did not meet the upper limit and considerations on both parts were given to understand the implications. In some cases the CO_2 specification limits were modified based on consultation with proponents and further development of studies on the source projects themselves which is discussed in the following section.

3.12 Further work: CO_2 specification implications for source projects

Subsequent to the completion of the CarbonNet Transport Pipeline Feasibility Study, further targeted studies were undertaken to understand the CO_2 capture and compression plant requirements of potential Victorian source projects, including the exploration of cost trade-offs for complying versus not complying with the proposed CO_2 specification. Whilst the details of these studies remain confidential, key insights provided by these studies included:

- Whole of system trade-off studies should be undertaken, and regularly reviewed and updated as project definition progresses
- For any given trace component, there tends to be a characteristic "marginal cost curve" which shows escalating costs per unit of removal as the targeted percentage removal a trace component increases (shown generically in Figure 3-8)

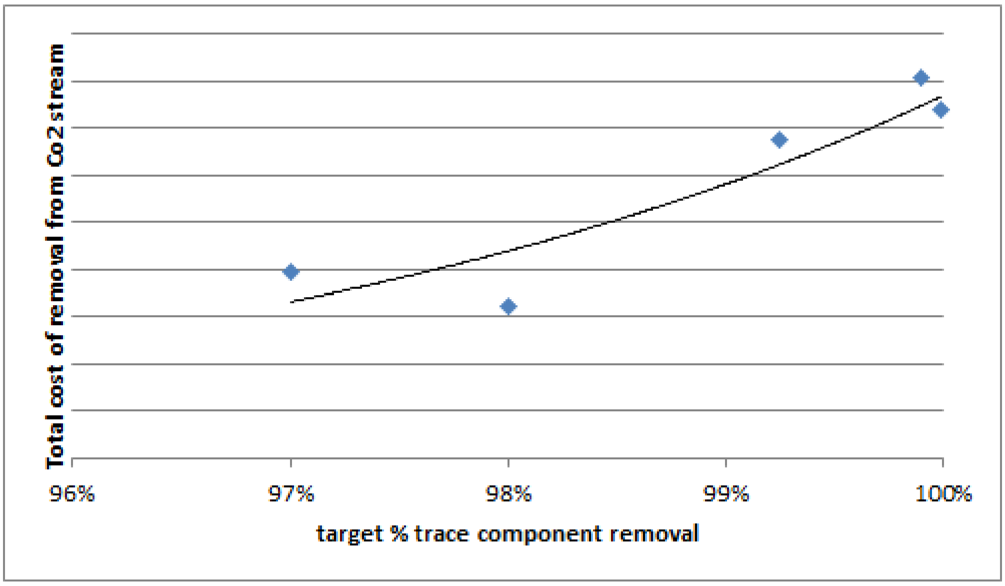

Figure 3-8 Target trace component removal

On a case-by-case basis, results may vary as to whether the most economical outcome (on a whole of system basis including the source and the transport and storage network) is in compliance with the existing CO_2 specification, or adjustment of the CO_2 specification is required to accept the inherent trace component concentration of the source in question. It is acknowledged that this is likely to be an iterative process, given that the techno-economic trade-off will affect the composition of the stream and that the level of impurities present will impact the overall phase envelope (T, P) that may impact the pipeline safety and operation design cases.

3.13 Reflection on the CO_2 specification and guidance

The development of a CO_2 specification for a CCS hub network is a complex and unique process due to the consideration of multiple factors/requirements across the entire CCS chain.

The resultant specification proposed for CarbonNet was an envelope specification consisting of an upper and lower limit for most of the components (with the exception of H_2O and other minor components). In an attempt to not discourage or prevent users from connecting into the network due to a very tight or restrictive CO_2 specification, a range was provided to allow prospective source proponents to understand their own commercial implications of achieving the upper or lower limit.

The upper limit was determined by the level that could be achieved by all of the capture technology groups as part of their business as usual (i.e. not requiring additional treatment or purification equipment) to minimise commercial implications for the potential source proponents. The lower limit considered STEL levels, Dynamis approach and subsequently the levels that could be achieved by the addition of commercially available technologies such as dehydration, desulphurisation, etc.

The approach used by CarbonNet differed from some of the guidance provided and from the more prescriptive type approaches that were used for point to point projects such E.On Kingsnorth, Scottish Power's Longannet, and the Dynamis project approach.

For trace components the guidance outlined that the desirable starting point was to be based on the Australian Occupational Health & Safety Short Term Exposure (STEL) limits and that investigations should be conducted to evaluate the technical and financial practicalities of achieving these levels. This was deemed to be a very conservative approach equivalent to assuming that the sensitive receptor is **inside the pipeline** (except that the CO_2 concentration at this point would be indicatively 33 times the CO_2 STEL).

Furthermore the Australian STEL levels are generally seen to be far lower than what can be achieved by commercially available purification equipment. Therefore if all components within the CO_2 stream were to comply with the Australian STEL, significant additional purification equipment would be required at each source project, adding substantial costs to each source project, in order to meet such tight limits. As a result the STEL levels were considered as a reference point only in the CO_2 specification development.

The Dynamis CO_2 Quality Recommendations report was also considered and the manner in which it addressed safety and toxicity limits amongst other items. Their approach to trace component limits from a health and safety perspective also made use of STEL limits as reference values, but based on a ratio of the STEL in an attempt to ensure the individual component levels were not more critical than the CO_2. However if this was to be considered then it would also require significant additional purification equipment at each source project. The limits associated with the main trace components and comparison of the STEL and the limit used by the Dynamis approach are summarised for information in Table 3.7.

Table 3.7 Trace components comparison of limits

COMPONENT	UNITS	LOWER	UPPER	STEL	DYNAMIS
CO_2	vol%	Balance of stream (> 93.5)		30000	N/A
H_2O	Max. ppmv		100	N/A	N/A
CO	Max. ppmv	900	5000	200	1333
H_2S	Max. ppmv	100	100[10]	15	100
SO_2	Max. ppmv	200	2000	5	33
NO_x	Max. ppmv	250	2500	5	33
HCN	Max. vol%	Subject to materiality threshold[11]		4.7	31

It is recognised that in future stage that further analysis is required to understand the implications of the increased limits (compared with STEL and Dynamis approach) of trace components through dispersion modelling of the upper and lower limits to determine the acceptability for atmospheric and storage basin releases from a health, safety and environment perspective.

The resultant CO_2 purity level was lower than the geoscience guidance provided (i.e. limit to < 2 vol%). From a health, safety and environment perspective the proposed limits of 5 vol% (upper limit) and 2 vol% (lower limit) of non condensables are not seen to present a risk. The proposed limits on non-condensables is most likely to impact only oxy-fuel streams (with pre-combustion and post-combustion technology groups generally achieving >98% CO_2) and the implications are a reduction in the transport and sequestration efficiency. In future stages more analysis needs to be completed on the geochemical and geomechanical issues associated with the other components.

The specified moisture limit of 100 ppmv is in line with the guidance to minimise the risk of free water and is based on readily achievable limits of most technologies. The introduction of an upper limit (such as 500 ppmv) and the implications on the dehydration technology required and associated capital and operating costs of the raised limit should be considered in the next phase. The effect on other components such as H_2S and SO_2 etc. would also need to be considered to avoid the risk of potential corrosion effects.

In summary the CarbonNet CO_2 specification has a lower and upper bound for most minor components. Marginal cost analysis of the impact between the lower and upper bounds of the CO_2 specification may be completed to assist in determining the components that influence the total cost so that the CO_2 specification is as accommodating as possible to all prospective sources.
Further consideration of potential source projects has identified a number of component limitations where techno-economic analysis of the trade-off between additional processing for the CO_2 sources and the impact on transport and storage would be beneficial. Assessment of the system acceptability of the preliminary specification will need to be completed in the next stages of the project.

[10] Studies subsequent to the pipeline Feasibility Study note the potential to relax to at least 150 ppmv.
[11] A materiality threshold is proposed for all Minor Components. The threshold proposed is Australian STEL values. Those Minor Components exceeding the STEL are to be considered on a case by case basis from a Health and Safety perspective.

3.14 Future considerations

The CO_2 specification defined for the project during the feasibility study proposed a range on relevant CO_2 impurities. It has been CarbonNet's intention to retain an envelope specification to allow a range of potential sources to participate (and an appropriate pricing mechanism to be developed). However, in order to determine absolute limits and finalise the specification envelope, the following activities are considered important for the subsequent project stage:

1. *Confirmation of Oxy-fired CO_2 specification:* The CO_2 specification Upper Limits are currently being influenced by the possible flue gas composition from an oxy-fired power plant with *limited* purification equipment. There is currently insufficient data available on this possible flue gas composition, particularly with respect to a techno-economic optimum for oxy-fired flue gas based on Victorian Brown Coal.
2. *Marginal cost analysis:* During the feasibility studies, the absolute cost impact of achieving the Upper and Lower CO_2 specification was evaluated. It is recognised that these costs are most relevant and best contextualised as a *marginal* cost to those of the base plant. This analysis would highlight those specification limits which are strong enablers to the economic viability of the base plant and which limits have little impact on the base plant's overall viability.
3. *Industry engagement and techno-economic analysis of the benefits of an increased H_2S specification:* The CarbonNet industry engagement process found that there *may* be benefits from the source proponent perspective to dispose of H_2S within the CO_2 stream. In developing the CO_2 specification the assumption was made that a separate H_2S and CO_2 stream would be generated by the pre-combustion process. However, there are processes that generate a combined stream of CO_2 and H_2S, these processes may provide techno-economic advantages for certain pre-combustion applications. Additionally there will be an economic trade-off between reduced costs for construction and operation of sulphur recovery plant or sulphur disposal equipment and the sale of sulphur products. Further industry engagement and a techno-economic analysis could be conducted to evaluate these merits. An increased H_2S specification will require careful analysis of the health and safety aspects and the implications on the pipeline design and economics.
4. *Confirmation of "Minor Components" limits:*
   - Dehydration equipment carryover: The proposed CO_2 specification implies that every source proponent will at a minimum be required to dehydrate their CO_2 stream. Particular attention to the carryover of minor constituents from dehydration equipment is therefore warranted. Major constituents of concern are glycol and Particulate Matter (PM) carryover from TEG units and desiccant beds respectively. This CO_2 specification document has grouped glycol with other "Minor Components" and limited these to STEL levels. Further analysis is to be conducted to test the reasonableness of this approach for glycol. PM BAU levels and Technically Achievable levels with filtration equipment are to be considered to determine appropriate PM ranges.
   - NOx control equipment carryover: The CO_2 specification recognises that a Selective Catalytic Reactor (SCR) is commonly employed technology for NOx control. This technology uses Ammonia injection to convert NOx species and, if not carefully controlled, may result in Ammonia slip. Ammonia is currently grouped with the "Minor Components" and limited to STEL levels. The reasonableness of this approach should be tested through industry engagement.
5. *System acceptability of proposed limits:* The proposed CO_2 specification ranges are subject to analysis to determine the maximum acceptable limits within that range. This will enable the range to be narrowed down to single values per impurity. These analysis include:
   - Pipeline Acceptability: Modelling of CO_2 stream to determine impact of impurities on phase envelope and critical point, pipeline fracture toughness, measurement length, etc.
   - Health, Safety and Environmental Acceptability: Dispersion modelling of upper and lower limits to determine Health and Safety acceptability for planned releases, unplanned releases and continuous leakages.

- Storage Basin Acceptability: Evaluation of impact on storage reservoir from a storage efficiency perspective as well as an environmental acceptability perspective. Particular consideration is warranted for groundwater contamination potential and geochemical suitability of the stream and the potential impacts on injectivity and storage formation leakage.
- The concept of stream blending or incorporation of tariff structures should be considered for the specific reasoning of relaxing Oxy-fuel requirements on inert components.

Future analysis should consider the worst case combination of impurities where appropriate.

6. *Consideration of the impact of the mix of impurities on the overall stream pressure and temperature phase diagram.* The impacts of the combination of components on the overall stream phase diagram needs to be considered for the normal operating conditions as well as the safety case / design for unplanned event, e.g. depressurisation / rupture, etc.
7. *Consideration of specification requirements during changing operating conditions.* The specification proposed is on the basis of “Normal” operating conditions. The impacts of operating conditions such as equipment failure, shut downs, line packing, venting etc. are to be considered in conjunction with the Operating Philosophy and the Risk Analysis.
8. *Consideration of the impact of toxic components within the CO_2 stream and the combined effects of components:* Components in the CO_2 stream which increase the toxicity will need to be considered and managed appropriately from a health, safety and environment perspective, as well as the implications on the measurement length. Similarly the combined effects of components within the stream (for e.g. the reaction between H_2S and SO_2 should be considered along with the impact on the pipeline and the measurement length.
9. *Consideration of the impacts of minor increases in the water specification to enable standard TEG units to be utilised.* The proposed moisture limit of 100 ppmv should be reviewed, and an upper limit of 200-500 ppmv considered with respect to the implications on the dehydration technology required and the capital and operating costs.

3.15 REFERENCES

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