

## QUALITY GUIDELINES FOR ENERGY SYSTEM STUDIES

# CO<sub>2</sub> Impurity Design Parameters

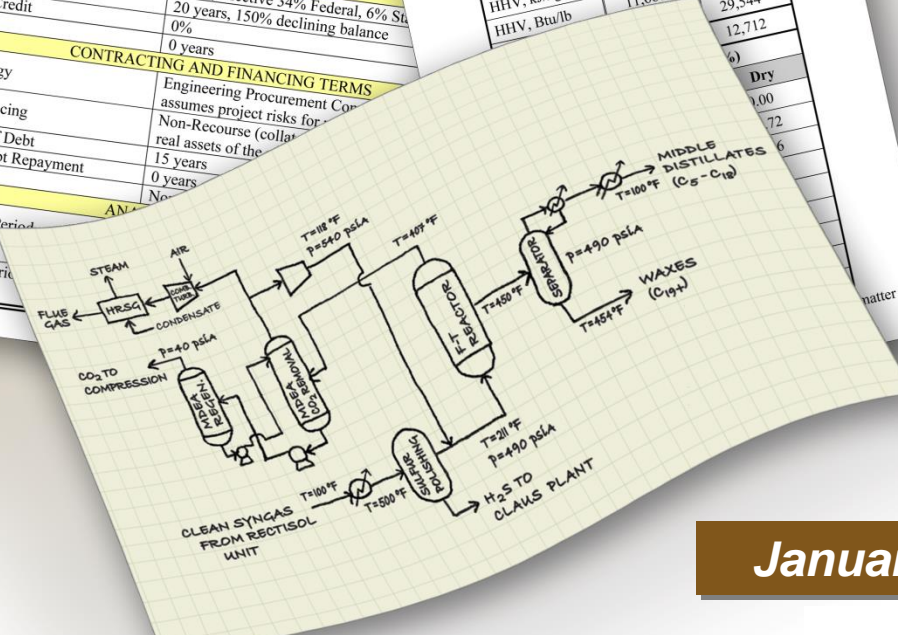
**Table 4: Global Economic Assumptions**

Parameter	Value
Income Tax Rate	TAXES
Capital Depreciation	38% (Effective 34% Federal, 6% State)
Investment Tax Credit	20 years, 150% declining balance
Tax Holiday	0%
<b>CONTRACTING AND FINANCING TERMS</b>	
Contracting Strategy	Engineering Procurement Construction (EPC) assumes project risks for the owner
Type of Debt Financing	Non-Recourse (collateralized by real assets of the project)
Repayment Term of Debt	15 years
Grace Period on Debt Repayment	0 years
Debt Reserve Fund	No
Capital Expenditure Period	ANALYSIS PERIOD
Operational Period	ANALYSIS PERIOD
Economic Analysis Period (IRROE)	ANALYSIS PERIOD

**Exhibit 2-3 Design Coal**

Rank	Bituminous	
Seam	Illinois No. 6 (Herrin)	
Source	Old Ben Mine	
Proximate Analysis (weight %) (Note A)		
	As Received	Dry
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Sulfur	2.51	2.82
HHV, kJ/kg	27,113	30,506
HHV, Btu/lb	11,666	13,126
		29,544
		12,712

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# **CO<sub>2</sub> Impurity Design Parameters**

**Final Report**

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## Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists	MEA	Monoethanolamine
AEP	American Electric Power	MESA	Mission Execution and Strategic Analysis
Ar	Argon	mg/m <sup>3</sup>	Milligram per cubic meter
C <sub>2</sub> H <sub>6</sub>	Ethane	mol%	Mole percent
C <sub>3</sub> +	Heavy hydrocarbons	MSDS	Material Safety Data Sheets
CCUS	Carbon capture, utilization, and sequestration	N <sub>2</sub>	Nitrogen
CH <sub>4</sub>	Methane	NETL	National Energy Technology Laboratory
CO	Carbon monoxide	NH <sub>3</sub>	Ammonia
CO <sub>2</sub>	Carbon dioxide	NIOSH	National Institute for Occupational Safety and Health
COS	Carbonyl sulfide	NO	Nitric oxide
DOE	Department of Energy	NO <sub>2</sub>	Nitrogen dioxide
EOR	Enhanced oil recovery	NO <sub>x</sub>	Oxides of nitrogen
EOS	Equations of State	O <sub>2</sub>	Oxygen
FeCO <sub>3</sub>	Iron carbonate	OSHA	Occupational Safety and Health Administration
FGD	Flue gas desulfurization	Part.	Particulates
H <sub>2</sub>	Hydrogen	ppb <sub>v</sub>	Parts per billion (volume)
H <sub>2</sub> O	Water	ppm	Parts per million
H <sub>2</sub> S	Hydrogen sulfide	ppm <sub>v</sub>	Parts per million (volume)
H <sub>2</sub> SO <sub>4</sub>	Sulfuric acid	psig	Pounds per square inch gauge
HCl	Hydrochloric acid	QGESS	Quality Guidelines for Energy System Studies
HCN	Hydrogen cyanide	SAS	Saline aquifer sequestration
HF	Hydrogen fluoride	SCR	Selective catalytic reduction
Hg	Mercury	SO <sub>2</sub>	Sulfur dioxide
HNO <sub>2</sub>	Nitrous acid	SO <sub>x</sub>	Sulfur dioxide
IDLH	Immediately Dangerous to Life and Health	TWA	Total Weighted Average
IEA	International Energy Agency	TWA8	8-hour time weighted average
IGCC	Integrated gasification combined cycle	U.S.	United States
KSI	Kilopound per square inch	vol%	Volume percent
lbs/MMSCF	Pounds per million standard cubic feet		

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# 1 Overview

This section of the Quality Guidelines for Energy System Studies (QGESS) provides recommended impurity limits for carbon dioxide (CO<sub>2</sub>) stream components for use in conceptual studies of CO<sub>2</sub> carbon capture, utilization, and storage systems. These limits were developed from information consolidated from numerous studies and are presented by component and application. Impurity levels are provided for carbon steel pipelines, sequestration through enhanced oil recovery (EOR), saline aquifer sequestration (SAS), and co-sequestration of CO<sub>2</sub> and hydrogen sulfide (H<sub>2</sub>S) in saline reservoirs. This QGESS is intended as a guideline only for conceptual studies under a generic scenario and should not be used for actual projects, which are likely to have requirements that differ from the generic scenario assumed herein.

Exhibit 2-1 provides the recommended limits for CO<sub>2</sub> stream impurities required by carbon steel transportation pipeline, EOR applications, and saline reservoirs. Each of the three design cases presents a design point and a range independent of the other design cases. For most impurities, the range indicates the maximum and minimum values found in the literature review and does not necessarily represent recommended limits; however, some represent an unofficial industry standard or the lack of information. In most cases, the design value matches the most restrictive constraint. Details for the design value and range for each impurity can be found in the subsections below Exhibit 2-1. Depending on the exact composition of the CO<sub>2</sub> stream, pipeline corrosion is of concern. Corrosion testing is difficult because of the multiple variables involved but is critical to determine standards for corrosion levels. (1) The impurity limits described in Section 2 are for isolated impurities and do not address the interactions between impurities.

The first set of data is for the compressed CO<sub>2</sub> transmission pipeline. Because it is assumed that the CO<sub>2</sub> stream to be sequestered remains at a constant 2,200 psig, the pipeline values are assumed to be independent of distance for EOR or SAS. However, it may be worthwhile in future efforts to characterize the effect of potential pressure losses on recommended ranges for certain components, as many components show different characteristics at different pressures.

EOR values are based on multiple EOR-recommended specifications and current EOR operations. Certain impurity limits will change depending on the oil quality and location. Also, certain health and safety hazards govern the design limitations. Refer to the notes for each contaminant listed in Section 2 for further detail.

SAS, like EOR, has multiple sources of information including the experience at American Electric Power's (AEP) Mountaineer plant—the first large-scale CCUS project.

Venting CO<sub>2</sub>, whether due to an upset condition in the plant or due to start-up of the CCUS system, can have detrimental effects, especially if certain impurities are present. The outermost column in Exhibit 2-1 indicates if the component could contribute to a hazardous or unlawful situation, depending on the quantity and the plant's emissions permit.

Attachment A is a list of 55 different CO<sub>2</sub> specifications found during the literature review. Pipeline design guides, pipe transportation specifications, and recommendations from multiple sources were used to evaluate and recommend limits based on the CO<sub>2</sub> source, such as plant type, air quality control systems, fuel used, gas transmission length, and other variables. This guideline does not attempt to tailor itself to every potential source variable, rather it is based on

the pipe and destination (whether a saline reservoir or oil reservoir) parameters necessary for CO<sub>2</sub> to be handled safely, efficiently, and cost effectively.

## 2 Gas Stream Composition

Exhibit 2-1 below lists the recommended maximum (or minimum when noted) CO<sub>2</sub> impurities for EOR or saline reservoir CCUS.

**Exhibit 2-1 CO<sub>2</sub> stream compositions recommended limits**

Component	Unit (Max unless otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO <sub>2</sub> & H <sub>2</sub> S Co-sequestration		Venting Concerns (See Section 3)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
CO <sub>2</sub>	vol% (Min)	95	90–99.8	95	90–99.8	95	90–99.8	95	20–99.8	Yes-IDLH 40,000 ppm <sub>v</sub>
H <sub>2</sub> O	ppm <sub>v</sub>	500	20–650	500	20–650	500	20–650	500	20–650	
N <sub>2</sub>	vol%	4	- 7	1	0.01 - 2	4	- 7	4	0.01–7	
O <sub>2</sub>	vol%	0.001	0.001–4	0.001	0.001–1.3	0.001	0.001–4	0.001	0.001–4	
Ar	vol%	4	0.01–4	1	0.01–1	4	0.01–4	4	0.01–4	
CH <sub>4</sub>	vol%	4	0.01–4	1	0.01–2	4	0.01–4	4	0.01–4	Yes-Asphyxiate, Explosive
H <sub>2</sub>	vol%	4	- 4	1	- 1	4	- 4	4	- 4	Yes-Asphyxiate, Explosive
CO	ppm <sub>v</sub>	35	10–5000	35	10–5000	35	10–5000	35	10–5000	Yes-IDLH 1,200 ppm <sub>v</sub>
H <sub>2</sub> S	vol%	0.01	0.002–1.3	0.01	0.002–1.3	0.01	0.002–1.3	75	10–77	Yes-IDLH 100 ppm <sub>v</sub>
SO <sub>2</sub>	ppm <sub>v</sub>	100	10–50000	100	10–50000	100	10–50000	50	10–100	Yes-IDLH 100 ppm <sub>v</sub>
NO <sub>x</sub>	ppm <sub>v</sub>	100	20–2500	100	20–2500	100	20–2500	100	20–2500	Yes-IDLH NO-100 ppm <sub>v</sub> , NO <sub>2</sub> -200 ppm <sub>v</sub>
NH <sub>3</sub>	ppm <sub>v</sub>	50	0–50	50	0–50	50	0–50	50	0–50	Yes-IDLH 300 ppm <sub>v</sub>
COS	ppm <sub>v</sub>	trace	trace	5	0–5	trace	trace	trace	trace	Lethal @ High Concentrations (>1,000 ppm <sub>v</sub> )

Component	Unit (Max unless otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO <sub>2</sub> & H <sub>2</sub> S Co-sequestration		Venting Concerns (See Section 3)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
C <sub>2</sub> H <sub>6</sub>	vol%	1	0–1	1	0–1	1	0–1	1	0–1	Yes-Asphyxiant, Explosive
C <sub>3</sub> +	vol%	<1	0–1	<1	0–1	<1	0–1	<1	0–1	
Part.	ppm <sub>v</sub>	1	0–1	1	0–1	1	0–1	1	0–1	
HCl	ppm <sub>v</sub>	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 50 ppm <sub>v</sub>
HF	ppm <sub>v</sub>	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 30 ppm <sub>v</sub>
HCN	ppm <sub>v</sub>	trace	trace	trace	trace	trace	trace	trace	trace	Yes-IDLH 50 ppm <sub>v</sub>
Hg	ppm <sub>v</sub>	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 2 mg/m <sup>3</sup> (organo)
Glycol	ppb <sub>v</sub>	46	0–174	46	0–174	46	0–174	46	0–174	
MEA	ppm <sub>v</sub>	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	MSDS Exp. Limits 3 ppm <sub>v</sub> , 6 mg/m <sup>3</sup>
Selexol	ppm <sub>v</sub>	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	

\*Not enough information is available to determine the maximum allowable amount

Several of the contaminant design limits were developed to address specific potential issues common to several contaminants. Examples of these include the following:

- Nitrogen (N<sub>2</sub>), Methane (CH<sub>4</sub>), and Hydrogen (H<sub>2</sub>) all have a lower critical temperature that would require increased pipe strength to minimize ductile fracture potential. (2)
- Non-condensables (N<sub>2</sub>, Oxygen (O<sub>2</sub>), Argon (Ar), CH<sub>4</sub>, H<sub>2</sub>) should be limited to reduce the amount of compression work; total non-condensables should be limited to less than 4 percent by volume. (3) In addition, non-condensables not only replace CO<sub>2</sub> in storage but reduce the density of the mixture causing total storage capacity to drop. (4) In addition, these non-condensables can affect the required well depth and injection pressure, as well as the injection lifetime of the well. It is estimated that for a flue gas of 80 mol% CO<sub>2</sub> and 20 mol% N<sub>2</sub> the pipeline capital cost and operational costs of the injection system would increase 10–25 percent. Additionally, the depth requirements increase 10–20 percent, and the flue gas would take up 2–4 times more pore space than a pure CO<sub>2</sub> stream. (5)

- Some of the component limits are based on the toxicity of the component (i.e., carbon monoxide (CO), H<sub>2</sub>S), which becomes a concern because of the potential for inadvertent releases. Toxic components with Immediately Dangerous to Life and Health (IDLH) concentration set by the National Institute for Occupational Safety and Health (NIOSH) (6) are listed in Exhibit 2-1. The IDLH concentration is not a short-term exposure limit to be encountered under normal working conditions, but a concentration from which escape may be made in 30 minutes without injury or irreversible health effects, and without deleterious/severe impediment to escape.
- EOR has specific limitations on O<sub>2</sub> concentration due to potential unwanted exothermic reactions with the hydrocarbons and limitations on H<sub>2</sub>S and sulfur dioxide (SO<sub>2</sub>), as they can be reproduced at the pumping well when the CO<sub>2</sub> front breaks through.

Additional information on specific contaminants is provided below.

## **2.1 CO<sub>2</sub>**

Once all impurities in the gas stream are identified and measured, the CO<sub>2</sub> component is arrived at by difference. The range was determined from multiple sources and can be affected by co-sequestration and levels of impurities. The highest concentration listed as a design parameter in the literature search that didn't include food-grade specifications is 99.8 percent. (7) The IDLH for CO<sub>2</sub> is 40,000 ppm. (6)

## **2.2 Water (H<sub>2</sub>O)**

Moisture content requirements vary widely and depend mostly on the amount of sulfur and other impurities in the gas stream. The lower range is typically for higher sulfur content and the higher range is for lower sulfur content. Sulfur and H<sub>2</sub>O can combine to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), which corrodes standard piping. Many moisture content specifications in the literature were derived from instrument air standards producing an unnecessarily stringent requirement. Multiple design parameters mention a maximum of 30 lbs/MMSCF (650 ppm<sub>v</sub>). 500 ppm<sub>v</sub> was chosen as a compromise among the multiple sources ranging from 20 ppm (8) to 30 lbs/MMSCF (650 ppm<sub>v</sub>) with many in the higher range. (2) Moisture content, however, is very site-specific depending on the other impurities such as oxides of nitrogen (NO<sub>x</sub>) and sulfur dioxide (SO<sub>x</sub>), which can form acids in the presence of H<sub>2</sub>O. (4) H<sub>2</sub>O in the presence of CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub> can form equipment damaging hydrates, depending on the pressure and temperature. Therefore, dehydration may be required at frequent intervals, particularly compression stages. (9) In carbon steel pipelines, "rigorously dry CO<sub>2</sub>" does not cause corrosion. However, the introduction of H<sub>2</sub>O has compounding effects on other impurities, such as O<sub>2</sub> and SO<sub>2</sub>. (10)

## **2.3 N<sub>2</sub>**

The design point for N<sub>2</sub> was taken from multiple sources with the range being set by pipeline specification. (2) (7) N<sub>2</sub> is a non-condensable species requiring additional compression work and has a concentration limit of typically less than 4 percent by volume (11) for most applications; however, it should also be noted that N<sub>2</sub> compression concentration could be as high as 7 percent by volume when coming from an oxycombustion system, but it is not recommended. (8) As mentioned earlier, the presence of N<sub>2</sub> can also require increased transport pipe strength due to ductility issues. For EOR applications, N<sub>2</sub> increases the miscibility pressure, making it more difficult to recover oil, which requires the design limit to be reduced to 1 percent by volume. (3)

## 2.4 O<sub>2</sub>

O<sub>2</sub> is another non-condensable species requiring additional compression work and a concentration limit of less than 4 percent by volume (11) for most applications. The German Federal Institute for Materials Research and Testing in Berlin conducted testing on pipe material with O<sub>2</sub> concentrations up to 6,600 ppm (0.66 percent by volume) and found no negative pipeline effects when SO<sub>2</sub> concentration was kept to a minimum. (12) However, O<sub>2</sub> in the presence of H<sub>2</sub>O can increase cathodic reactions causing thinning in the CO<sub>2</sub> pipeline. (13) Because of this, the typical standard found for pipeline designs is 0.01 percent by volume; however, operating pipelines tend to be even more conservative in the 0.001 to 0.004 percent by volume range. (8) The maximum O<sub>2</sub> content was set by specification (2), which is also used by the AEP Mountaineer project. (14) Preliminary conclusions from an ongoing National Energy Technology Laboratory (NETL) study indicate that the cost of a CO<sub>2</sub> purification system used to lower O<sub>2</sub> content doesn't vary significantly based on final O<sub>2</sub> concentration (10,100 or 1,000 ppm<sub>v</sub>).

The introduction of O<sub>2</sub> can inhibit the formation of iron carbonate (FeCO<sub>3</sub>), which is a protective layer that works to prevent corrosion. O<sub>2</sub> also provides cathodic reaction paths that lead to corrosion of carbon steel pipes. (10)

O<sub>2</sub> can also cause the injection points for EOR to overheat due to exothermic reactions with the hydrocarbons in the oil well. (15) In addition, high O<sub>2</sub> content can cause aerobic bacteria to grow in the reservoir and at the injection points. (16)

In sequestration applications, O<sub>2</sub> can react with SO<sub>2</sub> forming H<sub>2</sub>SO<sub>4</sub>, and nitric oxide (NO) forming nitrogen dioxide (NO<sub>2</sub>), which in H<sub>2</sub>O, could form nitrous acid (HNO<sub>2</sub>). Dissolved O<sub>2</sub> can also react with the caprock if it contains iron, manganese, and other metals. If dissolved ferrous ions are present in H<sub>2</sub>O within the formation, ferric oxide-hydrate, or ferric hydroxide, could form potentially plugging pore space as well. (4)

## 2.5 Ar

Ar is another non-condensable species requiring additional compression work and a typical limit of less than 4 percent by volume. (11) For EOR applications, Ar also increases the miscibility pressure, reducing its EOR limit to 1 percent by volume. (3)

## 2.6 CH<sub>4</sub>

CH<sub>4</sub> is another non-condensable species with a lower critical temperature requiring increased pipe strength due to ductility issues (2), and typically limited to concentrations of less than 4 percent by volume (3) as outlined earlier. The design point is taken from multiple sources. The CH<sub>4</sub> range was set by pipeline specification. (7) (2) CH<sub>4</sub> also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 percent by volume. (3)

## 2.7 H<sub>2</sub>

H<sub>2</sub> is another non-condensable species with a lower critical temperature requiring increased pipe strength due to ductility issues (2) and is typically limited to concentrations of less than 4 percent by volume (3) as outlined earlier. The design point was taken from multiple sources. The range was set by pipeline specification. (17) (8) H<sub>2</sub> also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 percent by volume. (3)

## 2.8 CO

CO is toxic and is thus controlled more stringently due to fears of unintended release into the atmosphere. The Total Weighted Average (TWA) concentration limit, set by NIOSH, is 35 ppm<sub>v</sub>. The TWA is the maximum allowable average concentration of a chemical in air for a normal 8-hour working day and 40-hour work week. (7) The range is set by the previous NETL Systems Analysis Guidelines as the minimum and the maximum was derived from Vattenfall. (7) Other specifications not addressing health hazards allow for concentrations in the 1000–5000 ppm<sub>v</sub> range. (18) (8) This toxic gas can also be a concern for EOR as it can be released at the pumping well when the CO<sub>2</sub> front breaks through. The IDLH concentration for CO is 1,200 ppm<sub>v</sub>. (6)

## 2.9 H<sub>2</sub>S

H<sub>2</sub>S is toxic and concentrations for non-sequestration applications are set at 0.01 percent by volume based on the IDLH concentration from NIOSH. (6) As discussed earlier, the IDLH concentration is not a short-term exposure limit to be encountered under normal working conditions, but a concentration from which escape may be made in 30 minutes without injury or irreversible health effects and without deleterious/severe impediment to escape. The targeted value of 0.01 percent by volume falls between the TWA recommendation from NIOSH of 10 ppm, which would be extremely costly to obtain, and the 200-ppm recommendation in *DYNAMIS CO<sub>2</sub> quality recommendations*. (11) The 200-ppm recommended limit was established based on health and safety effects by applying a safety factor of 5 on the known maximum exposure limit of 1000 ppm. (11) The maximum range limit of 1.3 percent by volume is from Vattenfall, one of the few references to specify a limit. (7) The H<sub>2</sub>S co-sequestration limit is based on NETL's Carbon Sequestration Systems Analysis Technical Note 10 (19) with the highest concentration, 77 percent, taken from the literature review. (20) It should be noted, however, that large quantities of H<sub>2</sub>S co-sequestered with CO<sub>2</sub> is done with the absence of O<sub>2</sub>. With the presence of SO<sub>2</sub>, elemental sulfur could be deposited in the rock formation's pores, especially if a catalyst is present in the rock formation, such as alumina or silica. The loss of sequestration space can be significant. (4) Because of its toxicity, H<sub>2</sub>S can be a concern for EOR, as it can be emitted at the pumping well when the CO<sub>2</sub> front breaks through.

## 2.10 SO<sub>2</sub>

The literature review indicates that a design level of 100 ppm<sub>v</sub> for SO<sub>2</sub> is easily achievable with current air quality control systems. (2) (11) Additionally, SO<sub>2</sub> is being investigated for co-sequestration with CO<sub>2</sub>. Preliminary reports predict that 5 percent by volume (50,000 ppm<sub>v</sub>) could be captured and have a negligible effect on the critical point of CO<sub>2</sub>. (21) The Global CCS Institute study on the effects of impurities on geological storage of CO<sub>2</sub> found that SO<sub>x</sub> can increase dissolution of the caprock, as it can form H<sub>2</sub>SO<sub>4</sub>; however, concentrations at 200 ppm or lower should have an insignificant impact. (4) The IDLH for SO<sub>2</sub> is 100 ppm<sub>v</sub> (6); therefore, this potentially toxic concentration can be a concern for EOR, as it can be reproduced at the pumping well when the CO<sub>2</sub> front breaks through. Vattenfall is one of a few entities to set this limit, so their value is used as the design target for SO<sub>2</sub> and the range's maximum amount. (7) Co-sequestration of H<sub>2</sub>S and CO<sub>2</sub> has a reduced maximum SO<sub>2</sub> than the other scenarios. This is because injection of H<sub>2</sub>S in conjunction with SO<sub>2</sub> can result in the deposition of elemental sulfur causing severe pore blocking. (4) In the absence of H<sub>2</sub>O, SO<sub>2</sub> will not corrode carbon steel pipes. (10)



## 2.11 NO<sub>x</sub>

The literature review indicates that a design level of 100 ppm for NO<sub>x</sub> is easily achievable with current air quality control systems. (17) (11) The NO<sub>x</sub> range was determined from a reference study that included the minimum and maximum values. (7) The Global CCS Institute study on the effects of impurities on geological storage of CO<sub>2</sub> found that NO<sub>x</sub> can increase dissolution of the caprock, as it can form NO; however, concentrations at 200 ppm<sub>v</sub> or lower should have an insignificant impact. (4) This toxic gas at higher concentrations can be a concern for EOR, as it can be reproduced at the pumping well when the CO<sub>2</sub> front breaks through. The IDLH limits for NO and NO<sub>2</sub> are 100 ppm<sub>v</sub> and 200 ppm<sub>v</sub>, respectively. (6)

## 2.12 Ammonia (NH<sub>3</sub>)

The allowed concentration at the AEP Mountaineer CCUS project is 50 ppm<sub>v</sub>. It is one of the few physical plants outlining an NH<sub>3</sub> concentration. Because of this, it was set as the design point and maximum amount. The IDLH for NH<sub>3</sub> is 300 ppm<sub>v</sub>. (6)

## 2.13 Carbonyl Sulfide (COS)

This toxin can be a concern for EOR, as it can be reproduced at the pumping well when the CO<sub>2</sub> front breaks through. Vattenfall is one of few entities to set this limit, so their value is used as the design target for COS and the range's maximum amount. (7) Although an IDLH has not been established for COS, it is known to be lethal at high concentrations (>1000 ppm<sub>v</sub>).

## 2.14 Hydrogen Cyanide (HCN)

These design parameters are established by Vattenfall. (7) Further research is needed as no other references were found other than ones that allowed trace amounts. This is a toxic compound with an IDLH of 50 ppm. (6)

## 2.15 Ethane (C<sub>2</sub>H<sub>6</sub>)

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (18) Although this is not a toxic compound, it is potentially explosive and might cause asphyxiation at high concentrations.

## 2.16 Heavy Hydrocarbons (C<sub>3</sub>+)

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (18)

## 2.17 Particulate

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (18)

## 2.18 Hydrochloric Acid (HCl)

Not enough information is available to determine the maximum allowable amount. Future research is needed. HCL is a toxic compound with an IDLH of 50 ppm<sub>v</sub>. (6)

## 2.19 Hydrogen Fluoride (HF)

Not enough information is available to determine the maximum allowable amount. Future research is needed. HF is a toxic compound with an IDLH of 30 ppm<sub>v</sub>. (6)

## 2.20 Mercury (Hg)

Not enough information is available to determine the maximum allowable amount. Future research is needed. Hg is a toxic compound with an IDLH of 10 mg/m<sup>3</sup> for compounds and 2 mg/m<sup>3</sup> for organomercury.

## 2.21 Glycol

Pipe specification limits were used because excess glycol carry-over can cause damage to seals and other components. (2) The range here is a value of zero to the maximum value of 174 ppb<sub>v</sub>, which is listed in the International Energy Agency (IEA) presentation referenced as an “Industrial Working Group Prelim Spec 2005.” (18)

## 2.22 Monoethanolamine (MEA)

Not enough information is available to determine the maximum allowable amount. Future research is needed. Although MEA is not an acute toxin and does not have an IDLH, Material Safety Data Sheets (MSDS) 8-hour time weighted average (TWA8) exposure limits are 3 ppm (TWA8 American Conference of Governmental Industrial Hygienists (ACGIH)) and 6 mg/m<sup>3</sup> (TWA8 Occupational Safety and Health Administration (OSHA)).

## 2.23 Selexol

Not enough information is available to determine the maximum allowable amount. Future research is needed.

# 3 Venting

Venting of CO<sub>2</sub> will occur during start-up of the CCUS system as well as during upset conditions of the plant. Standards for venting are complex and extremely area specific. Exhibit 2-1 outlines specific contaminants that could cause a hazard to the populace, such as the hydrocarbons and sulfur components. Toxic contaminant IDLH levels are presented in Exhibit 2-1. In addition, M.W. Kellogg considered other items (22):

- Local, national, and international regulations
- Contaminants in the stream—particularly NH<sub>3</sub> (ammonia slip), H<sub>2</sub>S, other sulfur components, and hydrocarbons—and how they affect the plant’s emissions permit
- Duration and frequency of venting
- Dispersion scenarios including a range of atmospheric conditions and proximity to population centers

M.W. Kellogg also indicated that atmospheric dispersion is the largest safety concern. If the dispersion does not occur rapidly enough, a dense CO<sub>2</sub> plume could drop to grade level and might cause asphyxiation. In that event, the recommendation is to flare the gas by adding natural gas to disperse the dense mixture before igniting it.

## 4 CCUS Technology-Specific Contaminants

Some contaminants are specific to the CO<sub>2</sub> capture technology employed. Below is a list of specific concerns and major contaminants associated with pre-combustion, post-combustion, and oxycombustion technologies.

### 4.1 Pre-Combustion

For the purposes of this guideline, pre-combustion capture from an integrated gasification combined cycle (IGCC) unit is assumed. Pre-combustion produces a fairly clean CO<sub>2</sub> stream. Organic impurities can still be present, as complete combustion that may remove them does not take place prior to CO<sub>2</sub> separation. These include CH<sub>4</sub>, HCN, COS, and other sulfur compounds. These compounds can cause corrosion and formation of hydrates during CCUS. Some of these impurities are also toxic to humans. (7)

Depending on how the physical process works, the Selexol or other acid gas removal solvents might be found in the gas stream; however, it is unknown what amount of Selexol will cause damage to the CCUS system or the reservoir itself. (7)

### 4.2 Post-Combustion

For the purpose of this guideline, a post-combustion MEA absorption system is assumed. CO<sub>2</sub> from a post-combustion process generally contains fewer numbers of different impurities than the other two technologies, as some may be consumed during combustion, as mentioned above. Still, the obvious NO<sub>x</sub>, SO<sub>x</sub>, and particulate can be a problem if the system does not have a properly functioning flue gas desulfurization (FGD), selective catalytic reduction (SCR), and/or baghouse. (23)

In addition, O<sub>2</sub> in the flue gas can lead to induced oxidative degradations of the MEA that can end up in the CO<sub>2</sub> product and cause corrosion. (24)

### 4.3 Oxycombustion

The CO<sub>2</sub> stream from an oxycombustion process contains the excess O<sub>2</sub> from the boiler. If no steps are taken to reduce O<sub>2</sub> content, it can exceed 3 percent by volume. Boiler air in-leakage increases the impurity concentrations by introducing non-condensables such as Ar and N<sub>2</sub> along with the O<sub>2</sub> that can become part of the CO<sub>2</sub> product. (25)

## 5 Research Needs

Several areas of research have been identified to better understand the impact of contaminants in supercritical CO<sub>2</sub>, and their effect on transport and underground sequestration systems.

Although there is a significant amount of information available on pure supercritical CO<sub>2</sub>, there is very limited data on mixtures with contaminants and H<sub>2</sub>O. Information/data needs have been identified in the following areas:

- Supercritical CO<sub>2</sub> Equations of State (EOS) for supercritical mixtures including speed of sound, entropy, enthalpy, viscosity, dew point
- Simpler/faster algorithms or lookup tables for supercritical CO<sub>2</sub> mixtures

- CO<sub>2</sub> data at 10–15 kilopound per square inch (KSI) (1kilopound=1,000 lb/in<sup>2</sup>) at 400–700 K
- CO<sub>2</sub> corrosion and compressibility data with contaminants and H<sub>2</sub>O
- A better understanding of the supercritical CO<sub>2</sub> gas phase dynamics and contaminant impacts on phase diagrams at critical points
- A better understanding of CO<sub>2</sub> dehydration in order to reduce corrosion and hydrate formation

Additional areas of research have also been identified to determine the impact of impurities on the underground sequestration of CO<sub>2</sub> including the following:

- Impact on plume dispersion
- The effect on the physical properties of storage formation, including the density and wettability of the rock; and the potential for contaminants to react in the formation, which may impact the functioning of the sequestration system
- The effect on potential anaerobes at injection depths and their potential for creating plugging and contamination issues
- Data on supercritical CO<sub>2</sub>-mixture storage in coal seams, including the effect on coal mechanical properties, swelling, CO<sub>2</sub> sorption, and CO<sub>2</sub> permeation
- Solubility data of SO<sub>2</sub> and H<sub>2</sub>S in brine for saline reservoir storage

Information needs have also been identified to better understand the impact of supercritical CO<sub>2</sub> contaminants on the transport pipeline. These include the following:

- Impact of pipeline pressure drops and temperature excursions
- Potential of additives to passivate corrosion
- Data on the response of elastomers (seals and gaskets) to supercritical CO<sub>2</sub> mixtures
- Design/methods to mitigate potential of boiling liquid expanding vapor explosion risks

Additional information also needs to be developed concerning the potential carryover of capture system components (NH<sub>3</sub>, amines) into the supercritical CO<sub>2</sub> stream.

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ATTACHMENT A - QGESS Literature Search Spreadsheet

Type Application Misc	NETL DESIGN BASIS					NON-NETL DESIGN BASIS												
	CCS	EOR		CCS	CCS	CCS	CCS	CCS	CCS	Generic		Generic	Generic	Generic	Generic			
	1	Remote destin.	Adjacent destin.	Remote destin.	Adjacent destin.	2	3	4	5	6	7	8	9	10	11	12	13	14
Current Systems Analysis Guidelines CO <sub>2</sub> Specification		Recommended CO <sub>2</sub> Sequestration Design Basis Remote EOR Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL Contact: Jared Cfermo.	Recommended CO <sub>2</sub> Sequestration Design Basis Adjacent EOR Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL	Recommended CO <sub>2</sub> Sequestration Design Basis Remote Geological Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL	Recommended CO <sub>2</sub> Sequestration Design Basis Adjacent Geological Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL	Design Basis CCS, Oxyfuel, Decker Coal Compression and drying 7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration"	Design Basis CCS, Oxyfuel, Decker Coal Partial Condensation 7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration"	Design Basis CCS, Oxyfuel, Decker Coal Part. Cond. And Distillation 7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration"	Design Basis CCS, Oxyfuel, Illinois #6 coal FGD, ESP, FF, Compression and drying ASME Turbo Expo 2007, "Impact of Gas Phase Impurities on CO <sub>2</sub> Compression"	Design Basis CCS or EOR, Oxyfuel, German Lignite Compression and drying, SO <sub>2</sub> removal Vattenfall Utveckling, Stockholm, Sweden "CO <sub>2</sub> quality requirement for a system with CO <sub>2</sub> capture, transport, and storage."	Design Basis CCS or EOR, Oxyfuel, German Lignite Compression and drying, CO <sub>2</sub> and SO <sub>2</sub> co-sequestration Vattenfall Utveckling, Stockholm, Sweden "CO <sub>2</sub> quality requirement for a system with CO <sub>2</sub> capture, transport, and storage."	Design Basis CCS or EOR, Post Combustion, German Lignite Compression and drying, MEA Absorption Vattenfall Utveckling, Stockholm, Sweden "CO <sub>2</sub> quality requirement for a system with CO <sub>2</sub> capture, transport, and storage."	Design Basis CCS or EOR, IGCC, German Lignite Compression and drying, Selecol process, H <sub>2</sub> S removal Vattenfall Utveckling, Stockholm, Sweden "CO <sub>2</sub> quality requirement for a system with CO <sub>2</sub> capture, transport, and storage."	Design Basis CCS or EOR, IGCC, German Lignite Compression and drying, Selecol process, CO <sub>2</sub> and H <sub>2</sub> S co-sequestration Vattenfall Utveckling, Stockholm, Sweden "CO <sub>2</sub> quality requirement for a system with CO <sub>2</sub> capture, transport, and storage."	Design Basis Carbon Steel piping transporting CO <sub>2</sub> ("Pipeline Design and Construction" ASME publication M Mohtpour)			
CO <sub>2</sub>	---	>95 vol%	>95 vol%	not limited	not limited	72.2 mol%	94.5 mol%	99.7 mol%	89.019 mol%	91 vol%	90 vol%	99.8 vol%	97.8 vol%	95.6 vol%				
Water	233°K (-40°F) dew point	150 ppmv	150 ppmv	150 ppmv	no free water					1400 ppmv	1400 ppmv	1400 ppmv	1400 ppmv	1400 ppmv	380 - 650 ppmv			
N <sub>2</sub>	<300 ppmv	<40000 ppmv	<40000 ppmv	not limited	not limited	198000 ppm wt	328000 ppm wt	0 mol%	19420 ppm wt	6100 ppmv	6000 ppmv	210 ppmv	300 ppmv	300 ppmv				
O <sub>2</sub>	<40 ppmv	<40 ppmv	<40 ppmv	<100 ppmv	<100 ppmv	48500 ppm wt	10800 ppm wt	0 mol%	47590 ppm wt	16000 ppmv	16000 ppmv	30 ppmv	unknown	unknown				
Ar	<10 ppmv	<10 ppmv	<10 ppmv	not limited	not limited	3.03 mol%	0.9 mol%	0 mol%	4.281 mol%	5.7 vol%	5.6 vol%	0.021 vol%	0.05 vol%	0.049 vol%				
CH <sub>4</sub>		<0.8 vol%	<0.8 vol%	<0.8 vol%	<4.0 vol%								350 ppmv	350 ppmv				
H <sub>2</sub>		uncertain	uncertain	uncertain	uncertain								1.7 vol%	1.7 vol%				
CO		<10 ppmv	<10 ppmv	not limited	not limited	200 ppm wt	0 mol%	0 mol%		unknown	unknown	10 ppmv	1700 ppmv	1700 ppmv				
H <sub>2</sub> S		<1.3 vol%	<1.3 vol%	<75 vol%									0.01 vol%	2.3 vol%				
SO <sub>2</sub>		<40 ppmv	<40 ppmv	30000 ppmv	30000 ppmv	1600 ppm wt	2300 ppm wt	2500 ppm wt		760 ppmv	15000 ppmv	10 ppmv						
NO										2500 ppmv	2400 ppmv	20 ppmv	unknown	unknown				
NO <sub>2</sub>		uncertain	uncertain	uncertain	uncertain	0.03 mol%	400 ppmwt	500 ppm wt										
TOTAL Hydrocarbons		<5 vol%	<5 vol%	<5 vol%	<5 vol%							30 ppmv	unknown	unknown				
NH <sub>3</sub>		<10 ppmv	<10 ppmv	not limited	not limited					trace	trace	unknown	30 ppmv	30 ppmv				
HCl										trace	trace	trace	trace	trace				
HF										trace	trace	trace	trace	trace				
HCN										trace	trace							
COS													<5 ppmv	<5 ppmv				
TOTAL Sulfur													<5 ppmv	<5 ppmv				
C <sub>2</sub> H <sub>6</sub>																		
C <sub>3</sub> H <sub>8</sub>																		
C <sub>4</sub> +																		
C <sub>5</sub> +																		
volatile hydrocarbons																		
TOTAL Inerts																		
Hg										trace	trace	trace	trace	trace				
Metals										trace	trace	trace	trace	trace				
Particulate										<1 ppm	<1 ppm	<1 ppm	<1 ppm	<1 ppm				
Glycol																		
MEA												unknown						
Selecol													unknown	unknown				
Delivery Pressure	152 bar																	
Delivery Temperature																		

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Type Application Misc	PIPE SPECIFICATIONS														
	Generic	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	Generic	Generic	Generic	Generic
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	Design Basis DYNAMIS quality recommendation  (Erika de Visser, "Dynamis CO <sub>2</sub> quality recommendations")	Design Basis ENCAP WP 1.1 EOR Guidelines  ("Oxy-fuel Combustion: Progress and Remaining Issues", A. Sarofim)	Design Basis ENCAP WP 1.1 Severe Limit Case  ("Oxy-fuel Combustion: Progress and Remaining Issues", A. Sarofim)	Kinder Morgan Pipeline Specification For EOR  (Kinder Morgan CO <sub>2</sub> Company, 2003)	PCOR Bell Creek Pipeline Specification for EOR  Coal Fired, Post Combustion  (DNV-RP-J202 recommend practice by DNV 2010)	PCOR Bell Creek Pipeline Specification for EOR  Coal Fired, Pre Combustion  (DNV-RP-J202 recommend practice by DNV 2010)	PCOR Bell Creek Pipeline Specification for EOR  Coal Fired, Oxyfuel  (DNV-RP-J202 recommend practice by DNV 2010)	PCOR Bell Creek Pipeline Specification for EOR  Gas Fired, Post Combustion  (DNV-RP-J202 recommend practice by DNV 2010)	PCOR Bell Creek Pipeline Specification for EOR  Gas Fired, Post Combustion  (DNV-RP-J202 recommend practice by DNV 2010)	PCOR Bell Creek Pipeline Specification for EOR  Gas Fired, Oxyfuel  (DNV-RP-J202 recommend practice by DNV 2010)	Dixon Consulting EOR August 2001  (Air Products presentation at 2006 gasification conference)	Dynamis specification for concentration limits as presented at the CCS conference Trendheim in 2007  (OosterKamp Presentation 2008 - R&D Foundation Polytec )	R&D Foundation Polytec Pipeline Specification  Amine  (OosterKamp Presentation 2008 - R&D Foundation Polytec)	R&D Foundation Polytec Pipeline Specification  Oxyfuel  (OosterKamp Presentation 2008 - R&D Foundation Polytec)	R&D Foundation Polytec Pipeline Specification  Pre-combustion  (OosterKamp Presentation 2008 - R&D Foundation Polytec)
CO <sub>2</sub>	>95.5%	>90 vol%	>95 vol%	>95 vol%								>95%	>99 vol%	>90 vol%	>95.6 vol%
Water	500 ppm	<500ppm	<5 ppm	<650 ppmv							<5C dp @ 300 psia	500 ppm	N/A	N/A	N/A
N <sub>2</sub>				<40000 ppmv	100 ppmv	300 - 6000 ppmv	37000 ppmv	100 ppmv	13000 ppmv	<42000 ppmv	<2.0% N2 & H2	<40000 ppmv	<0.17 vol%	70000 ppmv	6000 ppmv
O <sub>2</sub>		100 ppm	100 ppm	<10 ppmv	100 ppmv	300 - 6000 ppmv	37000 ppmv	100 ppmv	13000 ppmv	<41000 ppmv	<2.0 ppmv	Storage <4 vol%, EOR <100 ppm	<100 ppmv	<30000 ppmv	trace
Ar				0.01 vol%	0.03-0.6 vol%	3.7 vol%	0.01 vol%	1.3 vol%	<41000 ppmv			<4 vol%	trace	<5 vol%	<0.05 vol%
CH <sub>4</sub>	Storage <4 vol%, EOR <2 vol%			0	0.01 vol%	0	0	2.0 vol%	0	<1.0%	Storage <4 vol%, EOR <2 vol%	<100 ppm	---	350 ppm	
H <sub>2</sub>				0	0.8-2.0 vol%	0	0	1 vol%	0	<1.0%	<4 vol%	trace	trace	<3 vol%	
CO	2000 ppm			0	300-4000 ppmv	0	0	400 ppmv	0		2000 ppm	<10 ppm	trace	4000 ppmv	
H <sub>2</sub> S	200 ppm	<50 ppm	<5 ppm	<20 ppmv	0	0.01-0.6 vol%	0	0	<0.01 vol%	0	<100 ppmv	200 ppm	trace	trace	<3.4 vol%
SO <sub>2</sub>		<50 ppm	<5 ppm	100 ppmv	0	5000 ppmv	100 ppmv	0	100 ppmv	50000 ppmv	100 ppm	<10 ppm	25000 ppmv	---	
NO			<5 ppm	100 ppmv	0	100 ppmv	100 ppmv	0	100 ppmv						
NO <sub>2</sub>												100 ppm	<50 ppm	2500 ppmv	---
TOTAL Hydrocarbons				<5 vol%											
NH <sub>3</sub>															
HCl															
HF															
HCN			5 ppm												
COS		<50 ppm	10 ppm												
TOTAL Sulfur											<300 ppmv				
C <sub>2</sub> H <sub>6</sub>											<1.0%				
C <sub>3</sub> H <sub>8</sub>															
C <sub>4</sub> +													<100 ppm	---	<0.01 vol%
C <sub>5</sub> +											<1.0%				
volatile hydrocarbons															
TOTAL Inerts	<4 vol%	<4 vol%	<4 vol%												
Hg															
Metals															
Particulate															
Glycol				46 ppbv											
MEA															
Selexol															
Delivery Pressure															
Delivery Temperature															

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Type Application Misc	Operating Pipelines														
	Generic	Generic	Operating Pipelines												
	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
	Strawman Composite (Air Products presentation at 2006 gasification conference)	Industry working group Preliminary Specification 2005 (Air Products presentation at 2006 gasification conference)	Currently Operated Pipelines Canyon Reef Carriers (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Canyon Reef Carriers "Carbon Dioxide Capture and Storage" (Intergovernmental Panel on Climate Change (IPCC), 2005)	Currently Operated Pipelines Central Basin Pipeline (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Sheep Mountain (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Bravo Dome Source (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Cortez Pipeline (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Weyburn (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines Weyburn (Erika de Visser, "Dynamis CO2 quality recommendations")	Currently Operated Pipelines Jackson Dome (OosterKamp Presentation 2008 - R&D Foundation Polytec)	Currently Operated Pipelines McElmo Dome (WorleyParsons paper, "CO <sub>2</sub> Specifications for Pipeline Transportation")	Currently Operated Pipelines Laq CCS Pilot "The Laq CCS Pilot, a First" (J Morne, Total, 2012)	Currently Operated Pipelines Steiner (Erika de Visser, "Dynamis CO2 quality recommendations")	Currently Operated Pipelines Val Verde Basin (TX) Natural Gas (WorleyParsons paper, "CO <sub>2</sub> Specifications for Pipeline Transportation")
CO <sub>2</sub>	97% min	95% min	85-98%	>=95%	98.50%	96.8-97.4%	99.70%	95%	96%	96%	98.7-99.4%	>98%	90-93 vol%	93-96%	95%
Water	<1 ppv	<40C dp	50 ppm wt	<638.32 ppmv	240 ppm wt	120 ppm wt		240 ppm wt	20 ppm vol	<20 ppm		218 ppm	<10 ppmv	Saturated	
N <sub>2</sub>	30000 ppmv	<40000 ppmv	5000 ppmv	<4%	13000 ppmv	9000 ppmv	3000 ppmv	<40000 ppmv	<300 ppm	<300 ppm	trace		1-3 vol%		5000 ppmv
O <sub>2</sub>	2 ppmv	100 ppmv max		10 ppmv	<10 ppm spec				<50 ppm	<50 ppm			5-7 vol%		
Ar													1 vol%		
CH <sub>4</sub>	<1%		2-15% C6H14		0.20%	1.70%		1-5%	0.70%	0.70%	trace				5%
H <sub>2</sub>	<1%														
CO	5000 ppmv	1000 ppmv							1000 ppm	1000 ppm			<10 ppmv		
H <sub>2</sub> S	10-200 ppmv TED	10-200 ppmv Max	<200 ppm	<1500 ppmv	<20 ppm spec			0.002%	0.90%	9000 ppm	trace			Up to 150 ppm	100 ppm
SO <sub>2</sub>	50000 ppmv														
NO															
NO <sub>2</sub>															
TOTAL Hydrocarbons	<3%	5% Max		<5%							2.30%			0.5-2%	
NH <sub>3</sub>															
HCl															
HF															
HCN															
COS															
TOTAL Sulfur	10-200 ppmv			<1450 ppmv											
C <sub>2</sub> H <sub>6</sub>	<1%														
C <sub>3</sub> H <sub>8</sub>															
C <sub>4</sub> +						0.3-0.6%		trace	2.30%						
C <sub>5</sub> +	<1%														
volatile hydrocarbons															
TOTAL Inerts	<3%													3-5%	
Hg															
Metals															
Particulate															
Glycol		174 ppbv		<0.00004 L/m <sup>3</sup>											
MEA															
Selxol															
Delivery Pressure	2,220 psig	2,000 psia													
Delivery Temperature	120F max	120 F Max													

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Type Application Misc	MISC									
	46	47	48	49	50	51	52	53	54	55
	AEP Mountaineer CCS project	CO <sub>2</sub> Norway Compressor Specification (CO <sub>2</sub> Norway)	Canyon Reef Project Specification (Doctor and Palmer)	Dakota Gasification Company CO <sub>2</sub> experience (Perry and Eliason, 2005)	Acid Gas Injection experience (Carrol and Maddocks, 1999)	Typical Food Grade CO <sub>2</sub> Specification (Toromont Process Systems)	"Effect of Common Impurities on the Phase Behavior of Carbon-Dioxide-Rich Systems: Minimizing the Risk of Hydrate Formation and Two-Phase Flow" (A. Chapoy, Heriot-Watt University, 2011)	"Effects of Impurities on Geological Storage of CO <sub>2</sub> " (J. Wang, Global CCS Institute)	"Investigation of Corrosive Effects of Sulphur Dioxide, Oxygen and Water Vapour" (JGGC 2013, A. Ruhl)	"Developments and Innovation in carbon dioxide capture and storage technology" (A. Aspelund, Norway)
CO <sub>2</sub>	99.5 vol%	99.5 wt%	>95.0 vol%	96 wt%	22-90 vol% (water-free basis)	99.95 vol%				>95.5%
Water	245 ppm wt	Dew point <-5°C	No free water, dew point <-29°C	60 ppm wt	No free water	8 ppmv	<500 ppm land application, <250 ppm subsea application			500 ppm
N <sub>2</sub>	100 ppmv	4800 ppmv	<40000 ppmv	6000 ppm wt		40 ppmv				<4 vol% (all non-condensable gases)
O <sub>2</sub>	10 ppmv	<10 ppmv	<10 ppm wt	300 ppm wt		9 ppmv				50 ppm
Ar						20 ppmv				<4 vol% (all non-condensable gases)
CH <sub>4</sub>				0.3 wt%	0-4 vol% (water-free basis)	30 ppmv				Aquifer <4 vol% EOR <2 vol%
H <sub>2</sub>										<4 vol% (all non-condensable gases)
CO		<10 ppmv				2 ppmv				2000 ppm
H <sub>2</sub> S			<1500 ppmw	1 wt%	10-77 vol% (water-free basis)	0.5 ppmv				200 ppm
SO <sub>2</sub>		<10 ppmv				2 ppmv		200 ppm	650 ppm	
NO		<50 ppmv				2.5 ppmv				
NO <sub>2</sub>						2.5 ppmv		200 ppm		
TOTAL Hydrocarbons		<100 ppmv	<5 vol%	2 wt%		1 ppmv				
NH <sub>3</sub>	50 ppmv					2 ppmv				
HCl										
HF										
HCN										
COS										
TOTAL Sulfur										
C <sub>2</sub> H <sub>6</sub>										
C <sub>3</sub> H <sub>8</sub>						20 ppbv				20 ppbv
C <sub>2</sub> +*										
C <sub>3</sub> +*										
volatile hydrocarbons					Some ethane and propane	20 ppmv				20 ppmv
TOTAL Inerts										
Hg										
Metals										
Particulate										
Glycol										
MEA										
Selexol										
Delivery Pressure	1070 psig min									
Delivery Temperature	85 F Max									