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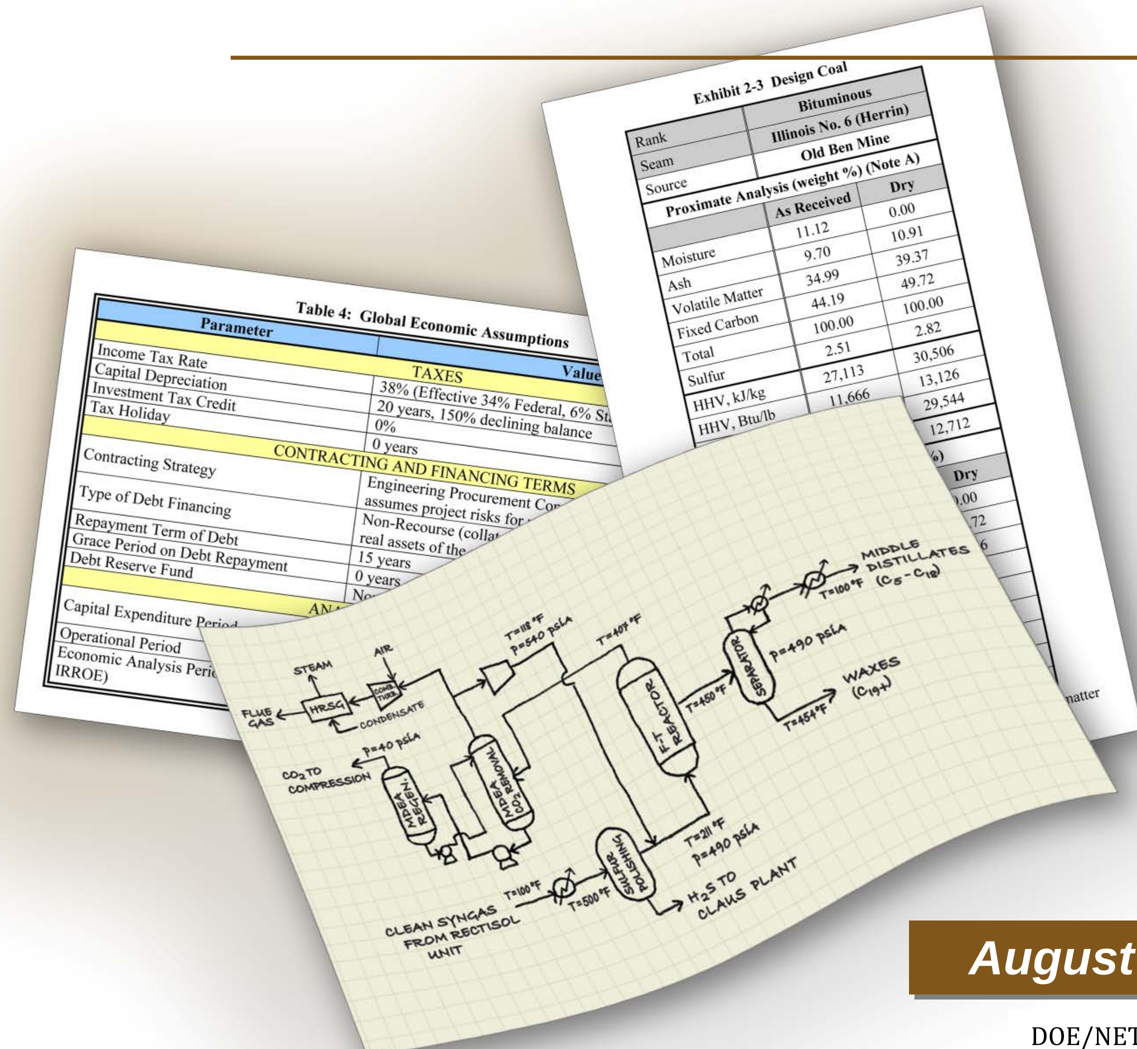
# QUALITY GUIDELINES FOR ENERGY SYSTEM STUDIES

# $CO_2$ Impurity Design Parameters

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# Disclaimer

# $CO_2$ Impurity Design Parameters

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**Draft Report**

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**Timothy Fout**, NETL Technical Project Monitor

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# Exhibits

# Acronyms and Abbreviations

| | |
|---|---|
| AEP | American Electric Power |
| CCUS | Capture utilization and sequestration |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| EOR | Enhanced oil recovery |
| EOS | Equations of State |
| FGD | Flue gas desulfurization |
| IDLH | Immediately Dangerous to Life and Health |
| IEA | International Energy Agency |
| IGCC | Integrated gasification combined cycle |
| $H_2$ | Hydrogen |
| $H_2S$ | Hydrogen sulfide |
| lbs/MMSCF | pounds per million standard cubic feet |
| MEA | Monoethanolamine |
| $N_2$ | Nitrogen |
| NETL | National Energy Technology Laboratory |
| NIOSH | National Institute for Occupational Safety and Health |
| NOx | Oxides of nitrogen |
| SAS | Saline aquifer sequestration |
| SCR | Selective catalytic reduction |
| TWA | Total Weighted Average |

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# 1 Overview

This section of the Quality Guidelines provides recommended impurity limits for $CO_2$ stream components for use in conceptual studies of $CO_2$ 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 $CO_2$ and $H_2S$ in saline reservoirs. This guideline is intended 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 contains the recommended limits for $CO_2$ stream impurities required by the transportation pipeline, by EOR applications, and by 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 the table. An extensive literature search revealed there is little experimental work done to date to identify the corrosion mechanisms that set the limitations on most of the impurities listed below. Corrosion testing is difficult because of the multiple variables involved but is critical to determine standards for corrosion levels. (1)

The first set of data is for the compressed $CO_2$ transmission pipeline. Because it is assumed that the $CO_2$ 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.

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 carbon capture utilization and sequestration (CCUS) project.

Venting $CO_2$, 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 farthest 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ to be handled safely, efficiently, and cost effectively.

# 2 Gas Stream Composition

Exhibit 2-1 below lists the recommended maximum (or minimum when noted) $CO_2$ impurities for EOR or saline reservoir CCUS.

**Exhibit 2-1 $CO_2$ stream compositions recommended limits**

| Component | Unit (Max unless Otherwise noted) | Carbon Steel Pipeline | | Enhanced Oil Recovery | | Saline Reservoir Sequestration | | Saline Reservoir $CO_2$ & $H_2S$ Co-sequestration | | Venting Concerns (See Section 3.0) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | |
| $CO_2$ | vol% (Min) | 95 | 90-99.8 | 95 | 90-99.8 | 95 | 90-99.8 | 95 | 20 – 99.8 | Yes-IDLH 40,000 ppmv |
| $H_2O$ | $ppm_v$ | 500 | 20 - 650 | 500 | 20 - 650 | 500 | 20 - 650 | 500 | 20 - 650 | |
| $N_2$ | vol% | 4 | 0.01 - 7 | 1 | 0.01 - 2 | 4 | 0.01 - 7 | 4 | 0.01 – 7 | |
| $O_2$ | 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 | |
| $CH_4$ | vol% | 4 | 0.01 – 4 | 1 | 0.01 – 2 | 4 | 0.01 – 4 | 4 | 0.01 – 4 | Yes-Asphyxiate, Explosive |
| $H_2$ | vol% | 4 | 0.01 - 4 | 1 | 0.01 – 1 | 4 | 0.01 – 4 | 4 | 0.02 – 4 | Yes-Asphyxiate, Explosive |
| CO | $ppm_v$ | 35 | 10 - 5000 | 35 | 10 - 5000 | 35 | 10 - 5000 | 35 | 10 - 5000 | Yes-IDLH 1,200 ppmv |
| $H_2S$ | 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 ppmv |
| $SO_2$ | $ppm_v$ | 100 | 10 - 50000 | 100 | 10 - 50000 | 100 | 10 - 50000 | 50 | 10 - 100 | Yes-IDLH 100 ppmv |
| $NO_X$ | $ppm_v$ | 100 | 20 - 2500 | 100 | 20 - 2500 | 100 | 20 - 2500 | 100 | 20 - 2500 | Yes-IDLH NO-100 ppmv, $NO_2$ - 200 ppmv |

| Component | Unit (Max unless Otherwise noted) | Carbon Steel Pipeline | | Enhanced Oil Recovery | | Saline Reservoir Sequestration | | Saline Reservoir $CO_2$ & $H_2S$ Co-sequestration | | Venting Concerns (See Section 3.0) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | Conceptual Design | Range in Literature | |
| $NH_3$ | $ppm_v$ | 50 | 0 - 50 | 50 | 0 - 50 | 50 | 0 - 50 | 50 | 0 - 50 | Yes-IDLH 300 ppmv |
| COS | $ppm_v$ | trace | trace | 5 | 0 - 5 | trace | trace | trace | trace | Lethal @ High Concentrations (>1,000 ppmv) |
| $C_2H_6$ | vol% | 1 | 0 - 1 | 1 | 0 - 1 | 1 | 0 - 1 | 1 | 0 - 1 | Yes- Asphyxiant, Explosive |
| $C_3$+ | vol% | <1 | 0 - 1 | <1 | 0 - 1 | <1 | 0 - 1 | <1 | 0 - 1 | |
| Part. | $ppm_v$ | 1 | 0 - 1 | 1 | 0 - 1 | 1 | 0 - 1 | 1 | 0 - 1 | |
| HCl | $ppm_v$ | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | Yes-IDLH 50 ppmv |
| HF | $ppm_v$ | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | Yes-IDLH 30 ppmv |
| HCN | $ppm_v$ | trace | trace | trace | trace | trace | trace | trace | trace | Yes-IDLH 50 ppmv |
| Hg | $ppm_v$ | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | Yes-IDLH 2 $mg/m^3$ (organo) |
| Glycol | $ppb_v$ | 46 | 0 - 174 | 46 | 0 - 174 | 46 | 0 - 174 | 46 | 0 - 174 | |
| MEA | $ppm_v$ | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | N.I.* | MSDS Exp. Limits 3 ppmv, 6 $mg/m^3$ |
| Selexol | $ppm_v$ | 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:

- $N_2$, $CH_4$, and $H_2$ all have a lower critical temperature that would require increased pipe strength to minimize ductile fracture potential (1)
- Non-condensables ($N_2$, $O_2$, Ar, $CH_4$, $H_2$) should be limited to reduce the amount of compression work; total non-condensables should be limited to less than 4 volume% (2) In

addition, non-condensables not only replace $CO_2$ in storage but reduce the density of the mixture causing total storage capacity to drop (3)

- Some of the limits are based on the toxicity of the component (CO, $H_2S$), which become 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) (4) 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 some specific limitations on $O_2$ concentration due to potential unwanted exothermic reactions with the hydrocarbons and limitations on $H_2S$ and $SO_2$, as they can be reproduced at the pumping well when the $CO_2$ front breaks through

Additional information on specific contaminants is provided below.

## 2.1 $CO_2$

Once all impurities in the gas stream are identified and measured, the $CO_2$ 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. (5) The IDLH for $CO_2$ is 40,000 ppm. (4)

## 2.2 $H_2O$

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. Improper combination of sulfur and water can form sulfuric acid, 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 $ppm_v$). 500 $ppm_v$ was chosen as a compromise among the multiple sources ranging from 20 ppm (6) and 30 lbs/MMSCF (650 $ppm_v$) with many in the higher range. (1) Moisture content, however, is very sight specific depending on the other impurities such as $NO_x$ and $SO_x$, which can form acids in the presence of water. (3)

## 2.3 $N_2$

The design point for nitrogen was taken from multiple sources with the range being set by pipeline specification. (1) (5) $N_2$ is a non-condensable species requiring additional compression work and has a concentration limit of typically less than 4 volume% (7) for most applications; however, it should also be noted that $N_2$ compression concentration could be as high as 7 volume% when coming from an oxycombustion system, but it is not recommended. (6) As mentioned earlier, the presence of $N_2$ can also require increased transport pipe strength due to ductility issues. For EOR applications, $N_2$ increases the miscibility pressure, making it more difficult to recover oil, which requires the design limit to be reduced to 1 volume%. (2)

## 2.4 $O_2$

Oxygen is another non-condensable species requiring additional compression work and a concentration limit of less than 4 volume% (7) for most applications. The BAM Federal Institute for Materials Research and Testing conducted testing on pipe material with $O_2$ concentrations up to 6,600 ppm (0.66% vol) and found no negative pipeline effects when $SO_2$ concentration was kept to a minimum. (9) However oxygen in the presence of $H_2O$ can increase cathodic reactions causing thinning in the $CO_2$ pipeline. (8) Because of this, the typical standard found for pipeline designs is 0.01 volume%; however, operating pipelines tend to be even more conservative in the 0.001 to 0.004 volume% range. (6) The maximum oxygen content was set by specification (1), which is also used by the AEP Mountaineer project. (9) Preliminary conclusions from an ongoing NETL study indicate that the cost of a $CO_2$ purification system used to lower $O_2$ content doesn't vary significantly based on final $O_2$ concentration (10, 100 or 1,000 ppmv).

Oxygen can also cause the injection points for EOR to overheat due to exothermic reactions with the hydrocarbons in the oil well. (10) In addition, high oxygen content can cause aerobic bacteria to grow in the reservoir and at the injection points. (11)

In sequestration applications, $O_2$ can react with $SO_2$ forming $H_2SO_4$, and NO forming $NO_2$, which in water could form $HNO_2$. Dissolved $O_2$ can also react with the cap rock if it contains iron, manganese, and other metals. If dissolved ferrous ions are present in water within the formation, ferric oxide-hydrate, or ferric hydroxide, could form potentially plugging pore space as well. (3)

## 2.5 Ar

Argon is another non-condensable species requiring additional compression work and a typical limit of less than 4 volume%. (7) For EOR applications, Ar also increases the miscibility pressure, reducing its EOR limit to 1 volume%. (2)

## 2.6 $CH_4$

Methane ($CH_4$) is another non-condensable species with a lower critical temperature requiring increased pipe strength due to ductility issues (1), and typically limited to concentrations of less than 4 volume% (2) as outlined earlier. The design point is taken from multiple sources. The methane range was set by pipeline specification. (5) (1) Methane also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 volume%. (2)

## 2.7 $H_2$

Hydrogen is another non-condensable species with a lower critical temperature requiring increased pipe strength due to ductility issues (1) and is typically limited to concentrations of less than 4 volume% (2) as outlined earlier. The design point was taken from multiple sources. The range was set by pipeline specification. (12) (6) Hydrogen also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 volume%. (2)

## 2.8 CO

Carbon monoxide (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. 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. (5) The range is set by the previous National Energy Technology Laboratory (NETL) Systems Analysis Guidelines as the minimum and the maximum was derived from Vattenfall.(5) Other specifications not addressing health hazards allow for concentrations in the 1000 – 5000 ppm range. (13)(6) This toxic gas can also be a concern for EOR as it can be released at the pumping well when the $CO_2$ front breaks through. The IDLH concentration for CO is 1,200 ppm. (4)

## 2.9 $H_2S$

Hydrogen sulfide ($H_2S$) is toxic and concentrations for non-sequestration applications are set at 0.01 volume% based on the IDLH concentration from NIOSH. (4) 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 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 $CO_2$ quality recommendations*. (7) 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. (7) The maximum range limit of 1.3 volume% is from Vattenfall, one of the few references to specify a limit. (5) The $H_2S$ co-sequestration limit is based on NETL's Carbon Sequestration Systems Analysis Technical Note 10 (14) with the highest concentration, 77 percent, taken from the literature review. (15) It should be noted, however, that large quantities of $H_2S$ co-sequestered with $CO_2$ is done with the absence of $O_2$. With the presence of $SO_2$, elemental sulphur 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. (3) Because of its toxicity, $H_2S$ can be a concern for EOR, as it can be emitted at the pumping well when the $CO_2$ front breaks through.

## 2.10 $SO_2$

The literature review indicates that a design level of 100 ppm for $SO_2$ is easily achievable with current air quality control systems. (1) (7) Additionally, $SO_2$ is being investigated for co-sequestration with $CO_2$. Preliminary reports predict that 5 volume% (50,000 ppmv) could be captured, and have a negligible effect on the critical point of $CO_2$. (16) The Global CCS institute study on the effects of impurities on geological storage of $CO_2$ found that $SO_x$ can increase dissolution of the caprock, as it can form sulphuric acid; however, concentrations at 200 ppm or lower should have an insignificant impact. (3) The IDLH for $SO_2$ is 100 ppm (4), therefore, this potentially toxic concentration can be a concern for EOR, as it can be reproduced at the pumping well when the $CO_2$ front breaks through. Vattenfall is one of a few entities to set this limit, so their value is used as the design target for $SO_2$ and the range's maximum amount. (5) Co-sequestration of H2S and CO2 has a reduced maximum SO2 than the other scenarios. This is because injection of H2S in conjunction with SO2 can result in the deposition of elemental sulphur causing severe pore blocking. (3)

## 2.11 $NO_x$

The literature review indicates that a design level of 100 ppm for oxides of nitrogen ($NO_x$) is easily achievable with current air quality control systems. (12) (7) The $NO_x$ range was determined from a reference study that included the minimum and maximum values. (5) The Global CCS institute study on the effects of impurities on geological storage of $CO_2$ found that $NO_x$ can increase dissolution of the caprock, as it can form nitric acid; however, concentrations at 200 ppm or lower should have an insignificant impact. (3) This toxic gas at higher concentrations can be a concern for EOR, as it can be reproduced at the pumping well when the $CO_2$ front breaks through. The IDLH limits for NO and $NO_2$ are 100 ppm and 200 ppm, respectively. (4)

## 2.12 $NH_3$

The allowed concentration at the AEP Mountaineer CCUS project is 50 ppmv. It is one of the few physical plants outlining an $NH_3$ concentration. Because of this, it was set as the design point and maximum amount. The IDLH for NH3 is 300 ppm. (4)

## 2.13 COS

This toxin can be a concern for EOR, as it can be reproduced at the pumping well when the $CO_2$ 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. (5) Although an IDLH has not been established for COS, it is known to be lethal at high concentrations (>1000 ppm).

## 2.14 HCN

These design parameters are established by Vattenfall. (5) 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. (4)

## 2.15 $C_2H_6$

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (13) Although this is not a toxic compound, it is potentially explosive and might cause asphyxiation at high concentrations.

## 2.16 $C_3$+

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (13)

## 2.17 Particulate

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite. (13)

## 2.18 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. (4)

### 2.19 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. (4)

### 2.20 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 $mg/m^3$ for compounds and 2 $mg/m^3$ for organomercury.

### 2.21 Glycol

Pipe specification limits were used because excess glycol carry-over can cause damage to seals and other components. (1) The range here is a value of zero to the maximum value of 174 ppbv, which is listed in the International Energy Agency (IEA) presentation referenced as an "Industrial Working Group Prelim Spec 2005." (13)

### 2.22 MEA

Not enough information is available to determine the maximum allowable amount. Future research is needed. Although monoethanolamine (MEA) is not an acute toxin and does not have an IDLH, MSDS 8 hour time weighted average (TWA8) exposure limits are 3 ppm (TWA8 ACGIH) and 6 $mg/m^3$ (TWA8 OSHA).

### 2.23 Selexol

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

## 3 Venting

Venting of $CO_2$ 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 (17):

- Local, national, and international regulations
- Contaminants in the stream -- particularly $NH_3$ (ammonia slip), $H_2S$, 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ stream. Organic impurities can still be present, as complete combustion that may remove them does not take place prior to $CO_2$ separation. These include $CH_4$, 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. (5)

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. (5)

## 4.2 Post-Combustion

For the purpose of this guideline, a post-combustion MEA absorption system is assumed. $CO_2$ 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 $NO_x$, $SO_x$, 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. (18)

In addition, oxygen in the flue gas can lead to induced oxidative degradations of the MEA that can end up in the $CO_2$ product and cause corrosion. (19)

## 4.3 Oxycombustion

The $CO_2$ stream from an oxycombustion process contains the excess oxygen from the boiler. If no steps are taken to reduce $O_2$ content, it can exceed 3 volume%. Boiler air in-leakage increases the impurity concentrations by introducing non-condensables such as Ar and $N_2$ along with the oxygen that can become part of the $CO_2$ product. (20)

# 5 Research Needs

Several areas of research have been identified to better understand the impact of contaminants in supercritical $CO_2$, and their effect on transport and underground sequestration systems.

Although there is a significant amount of information available on pure supercritical $CO_2$, there is very limited data on mixtures with contaminants and water. Information/data needs have been identified in the following areas:

- Supercritical $CO_2$ Equations of State (EOS) for supercritical mixtures including speed of sound, entropy, enthalpy, viscosity, dew point
- Simpler/faster algorithms or lookup tables for supercritical $CO_2$ mixtures

- $CO_2$ data at 10-15 KSI at 400-700 K
- $CO_2$ corrosion and compressibility data with contaminants and $H_2O$
- A better understanding of the supercritical $CO_2$ gas phase dynamics and contaminant impacts on phase diagrams at critical points
- A better understanding of $CO_2$ dehydration in order to reduce corrosion and methane hydrate formation

Additional areas of research have also been identified to determine the impact of impurities on the underground sequestration of $CO_2$ including the following:

- Impact on plume dispersion
- The effect on the physical properties of storage formation, including the density and wetability 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 $CO_2$-mixture storage in coal seams, including the effect on coal mechanical properties, swelling, $CO_2$ sorption and $CO_2$ permeation
- Solubility data of $SO_2$ and $H_2S$ in brine for saline reservoir storage

Information needs have also been identified to better understand the impact of supercritical $CO_2$ 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 $CO_2$ mixtures
- Design/methods to mitigate potential of boiling liquid vapor explosion (BLEVE) risks

Additional information also needs to be developed concerning the potential carryover of capture system components (ammonia, amines) into the supercritical $CO_2$ stream.

# Works Cited


1. *Corrosion of pipelines used for CO2 transport in CCS: Is it a real problem?* **Cole, Ivan.** s.l. : International Journal of Greenhouse Gas Control , 2011, Vol. 5.

2. **Havens, Ken.** *CO2 Transportation and EOR.* Houston, TX : Kinder Morgan CO2 Company, 2007.

3. **Global Oil Tools LLC.** Global Oil Tools - Enhanced Oil Recovery. *Global Oil Tools.* [Online] [Cited: January 24, 2011.] http://www.globaloiltoolsllc.com/html/2009103010474301.html.

4. **Wang, Jinsheng.** *Effects of Impurities on Geological Storage of Carbone Dioxide.* s.l. : Global CCS Institute, April 2011.

5. **National Institute for Occupational Safety and Health (NIOSH).** Chemical Listings and Documentation. *Center for Disease Control and Prevention.* [Online] September 30, 2011. http://www.cdc.gov/niosh/idlh/intridl4.html.

6. **Vattenfall Utveckling AB.** *CO2 Quality Requirement for a System with CO2 Capture, Transport and Storage.* Stockholm, Sweden : Vattenfall Utveckling AB.

7. **Oosterkamp, Antonie.** *CO2 Pipeline Transmission - a broad state of the art* - . s.l. : R&D Foundation Polytec, 2008. Presentation.

8. **DYNAMIS.** *DYNAMIS CO2 quality recommendations.* s.l. : European Commission, 2007. Project no: 019672.

9. *Investigation of corrosive effects of sulphur dioxide, oxygen and water vapour on pipeline steels.* **Ruhl, Aki.** Berlin : International Journal of Greenhouse Gas Control, 2013, Vol. 13.

10. **Shah, Minish.** *Capturing CO2 from Oxy-Fuel Combustion Flue Gas.* Cottbus, Germany : Praxair Inc., 2005.

11. **Spitznogle, Gary O.** CO2 Impurity Specification at AEP Mountaineer. [Email]. January 18, 2011.

12. **White, Vince.** *Purification of Oxyfuel-Derived CO2 for Sequestration or EOR.*

13. **Interstate Oil & Gas Compact Commission.** *A Policy, Legal, and Regulatory Evaluation of the Feasability of National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide.* Oklahoma City : Interstate Oil & Gas Compact Commission, 2010.

14. **Det Norske Veritas.** *Recommended Practice DNV-RP-J202; Design and Operation of CO2 Pipelines.* Hovik, Norway : Det Norske Veritas, 2010.

15. **Santos, Stanley.** Summary Notes on What is the Implication of CO2 Quality in its Design and Engineering of Pipeline Transport. Stockholm, Sweden : IEA Greenhouse Gas R&D Programme, October 2008.

16. **National Energy Technology Laboratory (NETL).** *Carbon Sequestration Systems Analysis Technical Note 10.* Pittsburgh : NETL, 2007.

17. **Carroll, John.** *Design Consideration for Acid Gas Injection.* Norman, Oklahoma : Gas Liquids Engineering Ltd., 1999.

18. **Crandell, LE.** *Dissolution Potential of SO2 CO-Injected with CO2 in Geologic Sequestration.* 2010. pp. 349-355.

19. **Weeks, David.** *Processing Considerations for Carbon Capture & Storage.* s.l. : M. W. Kellogg. Kellogg Paper No. 2059.

20. **Kanniche, Mohamed.** *Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture.* 2010. pp. 53-62.

21. **University of Cincinnati and EPA.** *Impacts of Flue Gas Impurities in Sequestered CO2 on Groundwater Sources: A Process Analysis and Implications for Risk Management.* Cincinnati : University of Cincinnati and EPA. Paper # 19.

22. **US Power Plant Laboratories.** Engineering Feasability and Economics of CO2 Sequestration/Use on an Existing Coal-Fired Power Plant: A Literature Review. Windsor, Connecticut : s.n., January 31, 2000.

23. **Visser, Erika de.** *Towards Hydrogen and Electricity Production with Carbon Dioxide Capture and Storage.* s.l. : European Commission, 2007.

24. **National Energy Technology Laboratory (NETL).** *Cost and Performance Baseline for Low-Rank Coal Fossil Energy Combustion Process Power Plants with and without CO2 Capture.* Pittsburgh : s.n., February 2010.

# ATTACHMENT A - QGESS Literature Search Spreadsheet

## (Page 1)

| Type / Application / Misc | NETL DESIGN BASIS<br>CCS | EOR<br>Remote destin. | EOR<br>Adjacent destin. | CCS<br>Remote destin. | CCS<br>Adjacent destin. | NON-NETL DESIGN BASIS<br>CCS | CCS | CCS | CCS | Generic | Generic | Generic<br>MEA | Generic<br>Selexol | Generic<br>Selexol | Generic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | Current Systems Analysis Guidelines $CO_2$ Specification | Recommended $CO_2$ Sequestration Design Basis<br>Remote EOR<br>Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL Contact: Jared Ciferno. | Recommended $CO_2$ Sequestration Design Basis<br>Adjacent EOR<br>Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL | Recommended $CO_2$ Sequestration Design Basis<br>Remote Geological<br>Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL | Recommended $CO_2$ Sequestration Design Basis<br>Adjacent Geological<br>Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL | Design Basis<br>CCS, Oxyfuel, Decker Coal<br>Compression and drying<br>7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration" | Design Basis<br>CCS, Oxyfuel, Decker Coal<br>Partial Condensation<br>7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration" | Design Basis<br>CCS, Oxyfuel, Decker Coal<br>Part. Cond. And Distillation<br>7th Annual conference on CCS (2008), "Considerations for Treating Oxy-Combustion Flue Gas Prior to Sequestration" | Design Basis<br>CCS, Oxyfuel, Illinois #6 coal<br>FGD,ESP,FF,Compression and drying<br>ASME Turbo Expo 2007, "Impact of Gas Phase Impurities on $CO_2$ Compression | Design Basis<br>CCS or EOR, Oxyfuel. German Lignite<br>Compression and drying, $SO_2$ removal<br>Vattenfall Utveckling, Stockholm, Sweden "$CO_2$ quality requirement for a system with $CO_2$ capture, transport, and storage. | Design Basis<br>CCS or EOR, Oxyfuel. German Lignite<br>Compression and drying, $CO_2$ and $SO_2$ co-sequestration<br>Vattenfall Utveckling, Stockholm, Sweden "$CO_2$ quality requirement for a system with $CO_2$ capture, transport, and storage. | Design Basis<br>CCS or EOR, Post Combustion, German Lignite<br>Compression and drying, MEA Absorption<br>Vattenfall Utveckling, Stockholm, Sweden "$CO_2$ quality requirement for a system with CO2 capture, transport, and storage. | Design Basis<br>CCS or EOR, IGCC, German Lignite<br>Compression and drying, Selexol process, $H_2S$ removal<br>Vattenfall Utveckling, Stockholm, Sweden "$CO_2$ quality requirement for a system with $CO_2$ capture, transport, and storage. | Design Basis<br>CCS or EOR, IGCC, German Lignite<br>Compression and drying, Selexol process, $CO_2$ and $H_2S$ co-sequestration<br>Vattenfall Utveckling, Stockholm, Sweden "$CO_2$ quality requirement for a system with $CO_2$ capture, transport, and storage. | Design Basis Carbon Steel piping transporting $CO_2$<br>("Pipeline Design and Construction" ASME publication M Mohitpour) |
| $CO_2$ | ---- | >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 |
| $N_2$ | <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 | |
| $O_2$ | <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% | |
| $CH_4$ | | <0.8 vol% | <0.8 vol% | <0.8 vol% | <4.0 vol% | | | | | | | | 350 ppmv | 350 ppmv | |
| $H_2$ | | 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 | |
| $H_2S$ | | <1.3 vol% | <1.3 vol% | <75 vol% | | | | | | | | | 0.01 vol% | 2.3 vol% | |
| $SO_2$ | | <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 | |
| $NO_2$ | | 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 | |
| $NH_3$ | | <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 | | <5 ppmv | <5 ppmv | |
| COS | | | | | | | | | | | | | <5 ppmv | <5 ppmv | |
| TOTAL Sulfur | | | | | | | | | | | | | | | |
| $C_2H_6$ | | | | | | | | | | | | | | | |
| $C_3H_6$ | | | | | | | | | | | | | | | |
| $C_2$+ | | | | | | | | | | | | | | | |
| $C_3$+ | | | | | | | | | | | | | | | |
| 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 | | | |
| Selexol | | | | | | | | | | | | | unknown | unknown | |
| Delivery Pressure | 152 bar | | | | | | | | | | | | | | |
| Delivery Temperature | | | | | | | | | | | | | | | |

# ATTACHMENT A - QGESS Literature Search Spreadsheet

## (Page 2)

| Type | PIPE SPECIFICATIONS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Application | Generic | EOR | EOR | EOR | EOR | EOR | EOR | EOR | EOR | EOR | EOR | Generic | Generic | Generic | Generic |
| Misc | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| | Design Basis DYNAMIS quality recommendation (Erika de Visser, "Dynamis $CO_2$ 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 $CO_2$ 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 Trondheim 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) |
| $CO_2$ | >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 |
| $N_2$ | | | | <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 |
| $O_2$ | | 100 ppm | 100 ppm | <10 ppmw | 100 ppmv | 300 - 6000 ppmv | 37000 ppmv | 100 ppmv | 13000 ppmv | <41000 ppmv | <2.0 ppmw | 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% |
| $CH_4$ | 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 |
| $H_2$ | | | | | 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 |
| $H_2S$ | 200 ppm | <50 ppm | <5 ppm | <20 ppmw | 0 | 0.01-0.6 vol% | 0 | 0 | <0.01 vol% | 0 | <100 ppmw | 200 ppm | trace | trace | <3.4 vol% |
| $SO_2$ | | <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 | | | | | |
| $NO_2$ | | | | | | | | | | | | 100 ppm | <50 ppm | 2500 ppmv | --- |
| TOTAL Hydrocarbons | | | | <5 vol% | | | | | | | | | | | |
| $NH_3$ | | | | | | | | | | | | | | | |
| HCl | | | | | | | | | | | | | | | |
| HF | | | | | | | | | | | | | | | |
| HCN | | | 5 ppm | | | | | | | | | | | | |
| COS | | <50 ppm | 10 ppm | | | | | | | | | | | | |
| TOTAL Sulfur | | | | | | | | | | | <300 ppmw | | | | |
| $C_2H_6$ | | | | | | | | | | | <1.0% | | | | |
| $C_6H_6$ | | | | | | | | | | | | | | | |
| $C_2$+ | | | | | | | | | | | | | <100 ppm | --- | <0.01 vol% |
| $C_3$+ | | | | | | | | | | | <1.0% | | | | |
| volatile hydrocarbons | | | | | | | | | | | | | | | |
| TOTAL Inerts | <4 vol% | <4 vol% | <4 vol% | | | | | | | | | | | | |
| Hg | | | | | | | | | | | | | | | |
| Metals | | | | | | | | | | | | | | | |
| Particulate | | | | | | | | | | | | | | | |
| Glycol | | | | 46 ppbv | | | | | | | | | | | |
| MEA | | | | | | | | | | | | | | | |
| Selexol | | | | | | | | | | | | | | | |
| Delivery Pressure | | | | | | | | | | | | | | | |
| Delivery Temperature | | | | | | | | | | | | | | | |

# ATTACHMENT A - QGESS Literature Search Spreadsheet

## (Page 3)

| Type<br>Application<br>Misc | Generic | Generic | Operating Pipelines | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 |
| | Strawman Composite<br>(Air Products presentation at 2006 gasification conference) | Industry working group Preliminary Specification 2005<br>(Air Products presentation at 2006 gasfication conference) | Currently Operated Pipelines<br>Canyon Reef Carriers<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Canyon Reef Carriers<br>"Carbon Dioxide Capture and Storage" (Intergovernmental Panel on Climate Change (IPCC), 2005) | Currently Operated Pipelines<br>Central Basin Pipeline<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Sheep Mountain<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Bravo Dome Source<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Cortez Pipeline<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Weyburn<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>Weyburn<br>(Erika de Visser, "Dynamis CO2 quality recommendations") | Currently Operated Pipelines<br>Jackson Dome<br>(OosterKamp Presentation 2008 - R&D Foundation Polytec) | Currently Operated Pipelines<br>McElmo Dome<br>(WorleyParsons paper, "$CO_2$ Specifications for Pipeline Transportation") | Currently Operated Pipelines<br>Lacq CCS Pilot<br>"The Lacq CCS Pilot, a First" (J Monne, Total, 2012) | Currently Operated Pipelines<br>Sleipner<br>(Erika de Visser, "Dynamis CO2 quality recommendations") | Currently Operated Pipelines<br>Val Verde Basin (TX) Natural Gas<br>(WorleyParsons paper, "$CO_2$ Specifications for Pipeline Transportation") |
| $CO_2$ | 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 | |
| $N_2$ | 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 |
| $O_2$ | 2 ppmv | 100 ppmv max | | 10 ppmw | <10 ppm spec | | | | <50 ppm | <50 ppm | | | 5-7 vol% | | |
| Ar | | | | | | | | | | | | | 1 vol% | | |
| $CH_4$ | <1% | | 2-15% C6H14 | | 0.20% | 1.70% | | 1-5% | 0.70% | 0.70% | trace | | | | 5% |
| $H_2$ | <1% | | | | | | | | | | | | | | |
| CO | 5000 ppmv | 1000 ppmv | | | | | | | 1000 ppm | 1000 ppm | | | <10 ppmv | | |
| $H_2S$ | 10-200 ppmv TBD | 10-200 ppmv Max | <200 ppm | <1500 ppmw | <20 ppm spec | | | 0.002% | 0.90% | 9000 ppm | trace | | | Up to 150 ppm | 100 ppm |
| $SO_2$ | 50000 ppmv | | | | | | | | | | | | | | |
| NO | | | | | | | | | | | | | | | |
| $NO_2$ | | | | | | | | | | | | | | | |
| TOTAL Hydrocarbons | <3% | 5% Max | | <5% | | | | | | 2.30% | | | | 0.5-2% | |
| $NH_3$ | | | | | | | | | | | | | | | |
| HCl | | | | | | | | | | | | | | | |
| HF | | | | | | | | | | | | | | | |
| HCN | | | | | | | | | | | | | | | |
| COS | | | | | | | | | | | | | | | |
| TOTAL Sulfur | 10-200 ppmv | | | <1450 ppmw | | | | | | | | | | | |
| $C_2H_6$ | <1% | | | | | | | | | | | | | | |
| $C_3H_8$ | | | | | | | | | | | | | | | |
| $C_2$+ | | | | | | 0.3-0.6% | | trace | 2.30% | | | | | | |
| $C_3$+ | <1% | | | | | | | | | | | | | | |
| volatile hydrocarbons | | | | | | | | | | | | | | | |
| TOTAL Inerts | <3% | | | | | | | | | | | | | 3-5% | |
| Hg | | | | | | | | | | | | | | | |
| Metals | | | | | | | | | | | | | | | |
| Particulate | | | | | | | | | | | | | | | |
| Glycol | | 174 ppbv | | <0.00004 L/m^3 | | | | | | | | | | | |
| MEA | | | | | | | | | | | | | | | |
| Selexol | | | | | | | | | | | | | | | |
| Delivery Pressure | 2,220 psig | 2,000 psia | | | | | | | | | | | | | |
| Delivery Temperature | 120F max | 120 F Max | | | | | | | | | | | | | |

# ATTACHMENT A - QGESS Literature Search Spreadsheet

## (Page 4)

| Type / Application / Misc | MISC | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| | AEP Mountaineer CCS project | $CO_2$ Norway Compressor Specification ($CO_2$ Norway) | Canyon Reef Project Specification (Doctor and Palmer) | Dakota Gasfication Company $CO_2$ experience (Perry and Eliason, 2005) | Acid Gas Injection experience (Carrol and Maddocks, 1999) | Typical Food Grade $CO_2$ 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 CO2" (J. Wang, Global CCS Institute) | "Investigation of Corrosive Effects of Sulphur Dioxide, Oxygen and Water Vapour" (IJGGC 2013, A. Ruhl) | "Developments and Innovation in carbon dioxide capture and storage technology" (A. Aspelund, Norway) |
| $CO_2$ | 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 |
| $N_2$ | 100 ppmv | 4800 ppmv | <40000 ppmv | 6000 ppm wt | | 40 ppmv | | | | < 4 vol% (all non-condensable gases) |
| $O_2$ | 10 ppmv | <10 ppmv | <10 ppm wt | 300 ppm wt | | 9 ppmv | | | | 50 ppm |
| Ar | | | | | | 20 ppmv | | | | < 4 vol% (all non-condensable gases) |
| $CH_4$ | | | | 0.3 wt% | 0-4 vol% (water-free basis) | 30 ppmv | | | | Aquifer < 4 vol% EOR < 2 vol% |
| $H_2$ | | | | | | | | | | < 4 vol% (all non-condensable gases) |
| CO | | <10 ppmv | | | | 2 ppmv | | | | 2000 ppm |
| $H_2S$ | | | <1500 ppmw | 1 wt% | 10-77 vol% (water-free basis) | 0.5 ppmv | | | | 200 ppm |
| $SO_2$ | | <10 ppmv | | | | 2 ppmv | | 200 ppm | 650 ppm | |
| NO | | <50 ppmv | | | | 2.5 ppmv | | | | |
| $NO_2$ | | | | | | 2.5 ppmv | | 200 ppm | | |
| TOTAL Hydrocarbons | | <100 ppmv | <5 vol% | 2 wt% | | 1 ppmv | | | | |
| $NH_3$ | 50 ppmv | | | | | 2 ppmv | | | | |
| HCl | | | | | | | | | | |
| HF | | | | | | | | | | |
| HCN | | | | | | | | | | |
| COS | | | | | | | | | | |
| TOTAL Sulfur | | | | | | | | | | |
| $C_2H_6$ | | | | | | | | | | |
| $C_6H_6$ | | | | | | 20 ppbv | | | | 20 ppbv |
| $C_2$+ | | | | | | | | | | |
| $C_3$+ | | | | | | | | | | |
| 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 | | | | | | | | | |