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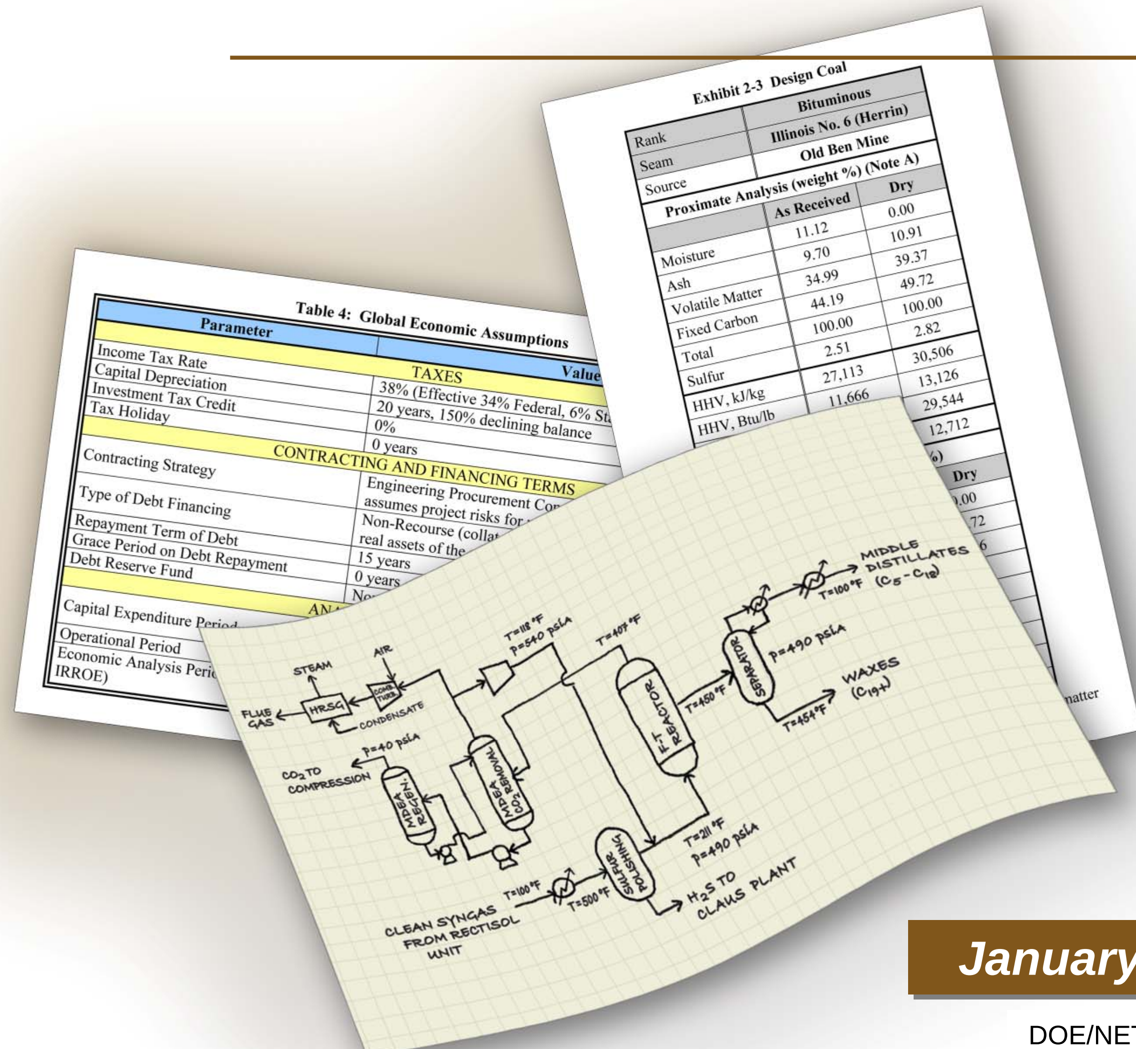
QUALITY GUIDELINES FOR ENERGY SYSTEM STUDIES

CO_2 Impurity Design Parameters



January 2012

DOE/NETL-341/011212

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Disclaimer

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 reservoir sequestration, 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 gives the recommended limits for CO_2 stream impurities required by the transportation pipeline, by EOR applications, and by saline reservoir. 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. Specific details of the design and range information can be found in the subsections below the table broken out by the given impurity.

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 43 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_{wt}	300	20 - 650	300	20 - 650	300	20 - 650	300	20 - 650	
N_2	vol%	4	0.01 - 7	1	0.01 - 2	4	0.01 - 7	4	0.01 – 7	
O_2	vol%	4	0.01 – 4	0.01	0.001 – 1.3	4	0.01 – 4	4	0.01 – 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	100	10 - 50000	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:

- N_2, CH_4, and H_2 all have a lower critical temperature that would require increased pipe strength to minimize ductile fracture potential (4).
- 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 % (6)

- 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) (1) 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% (2). The IDLH for CO_2 is 40,000 ppm (1).

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. A compromise value of 300 ppm_{wt} was chosen among the multiple sources ranging from 20 ppm (3) and 30 lbs/MMSCF (650 ppm_{wt}) (4).

2.3 N_2

The design point for nitrogen was taken from multiple sources with the range being set by pipeline specification (4, 2). N_2 is a non-condensable species requiring additional compression work and has a concentration limit of typically less than 4 volume% (5) 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 (3). 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% (6).

2.4 O_2

Oxygen is another non-condensable species requiring additional compression work and a concentration limit of less than 4 volume% (5) for most applications. Oxygen in the presence of H_2O can increase cathodic reactions causing thinning in the CO_2 pipeline (7). 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 (3). The maximum oxygen content was set by specification (4), which is also used by the AEP Mountaineer project (8).

Oxygen can also cause the injection points for EOR to overheat due to exothermic reactions with the hydrocarbons in the oil well (9). In addition, high oxygen content can cause aerobic bacteria to grow in the reservoir and at the injection points (10). For these reasons, the oxygen contaminant design target and allowable range is lower for EOR (9).

2.5 Ar

Argon is another non-condensable species requiring additional compression work and a typical limit of less than 4 volume% (5). For EOR applications, Ar also increases the miscibility pressure, reducing its EOR limit to 1 volume% (6).

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 (4) and typically limited to concentrations of less than 4 volume% (6) as outlined earlier. The design point is taken from multiple sources. The methane range was set by pipeline specification (2) (4). Methane also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 volume% (6).

2.7 H_2

Hydrogen is another non-condensable species with a lower critical temperature requiring increased pipe strength due to ductility issues (4) and is typically limited to concentrations of less than 4 volume% (6) as outlined earlier. The design point was taken from multiple sources. The range was set by pipeline specification (11) (3). Hydrogen also increases the miscibility pressure, making it more difficult to recover oil, so the EOR limit is reduced to 1 volume% (6).

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 (2). 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 (2). Other specifications not addressing health hazards allow for concentrations in the 1000 – 5000 ppm range (12), (3). 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 (1).

2.9 H_2S

Hydrogen sulfide (H_2S) is toxic and concentrations for non-sequestration applications are set at 0.01 vol% based on the IDLH concentration from NIOSH (1). 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 0.01vol% falls between the TWA recommendation from NIOSH of 10 ppm, which would be extremely costly to obtain and the 200 ppm recommendation in reference (5). 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 (5). The maximum range limit of 1.3 vol% is from Vattenfall, one of the few references to specify a limit (2). The H_2S co-sequestration limit is based on NETL's Carbon Sequestration Systems Analysis Technical Note 10 (13) with the highest concentration, 77%, taken from the literature review (14). 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 (4) (5). 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 (15). The IDLH for SO_2 is 100 ppm (1), 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 (2).

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 (11) (5). The NOx range was determined from a reference study that included the minimum and maximum values (2). 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 (1).

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 (1).

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 (2). 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 (2). Further research is needed as no other references where found other than ones that allowed trace amounts. This is a toxic compound with an IDLH of 50 ppm (1).

2.15 C_2H_6

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite (12). 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 (12).

2.17 Particulate

These design parameters are based on Dixon Consulting EOR, Dakota Gasification specification, and Strawman Composite (12).

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 (1).

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 (1).

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 organo mercury.

2.21 Glycol

Pipe specification limits were used because excess glycol carry-over can cause damage to seals and other components (4). The range here is a value of zero to the maximum value of 174 ppbv, which is listed in the IEA presentation referenced as an "Industrial Working Group Prelim Spec 2005" (12).

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 populous 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 (16):

- 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 (2).

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 (2).

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 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 FGD, SCR, and/or baghouse (17).

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. (18).

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 vol%. 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 (19).

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:

- 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:

- 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.

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ATTACHMENT A - QGESS Literature Search Spreadsheet

(Page 1)

QGESS Literature Search Results

Type	NETL DESIGN BASIS					NON-NETL DESIGN BASIS								
Application	CCS	EOR	EOR	CCS	CCS	CCS	CCS	CCS	CCS	Generic	Generic	Generic	Generic	Generic
Misc		Remote destin.	Adjacent destin	Remote destin.	Adjacent destin.							MEA	Selexol	Selexol
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Current Systems Analysis Guidelines CO_2 Specification	Recommended CO_2 Sequestration Design Basis Remote EOR Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL Contact: Jared Ciferno.	Recommended CO_2 Sequestration Design Basis Adjacent EOR Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL	Recommended CO_2 Sequestration Design Basis Remote Geological Carbon Sequestration Systems Analysis Technical Note No. 10, Revised March 2007, NETL	Recommended CO_2 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_2 Compression	Design Basis CCS or EOR, Oxyfuel. German Lignite Compression and drying, SO_2 removal Vattenfall Utveckling, Stockholm, Sweden "CO_2 quality requirement for a system with CO_2 capture, transport, and storage.	Design Basis CCS or EOR, Oxyfuel. German Lignite Compression and drying, CO_2 and SO_2 co-sequestration Vattenfall Utveckling, Stockholm, Sweden "CO_2 quality requirement for a system with CO_2 capture, transport, and storage.	Design Basis CCS or EOR, Post Combustion, German Lignite Compression and drying, MEA Absorption Vattenfall Utveckling, Stockholm, Sweden "CO_2 quality requirement for a system with CO2 capture, transport, and storage.	Design Basis CCS or EOR, IGCC, German Lignite Compression and drying, Selexol process, H_2S removal Vattenfall Utveckling, Stockholm, Sweden "CO_2 quality requirement for a system with CO_2 capture, transport, and storage.	Design Basis CCS or EOR, IGCC, German Lignite Compression and drying, Selexol process, CO_2 and H_2S co-sequestration Vattenfall Utveckling, Stockholm, Sweden "CO_2 quality requirement for a system with CO_2 capture, transport, and storage.
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
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_6H_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

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QGESS Literature Search Results

Type / Application / Misc														
	PIPE SPECIFICATIONS													
	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	Generic	Generic	Generic	Generic	Generic	Generic
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	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)	Straw man Composite (Air Products presentation at 2006 gasification conference)	Industry working group Preliminary Specification 2005 (Air Products presentation at 2006 gasification conference)
CO_2	>95 vol%								>95%	>99 vol%	>90 vol%	>95.6 vol%	97% min	95% min
Water	654 ppm							<-5C dp @ 300 psia	500 ppm	N/A	N/A	N/A	<1 ppv	<-40C dp
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	30000 ppmv	<40000 ppmv
O_2	<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	2 ppmv	100 ppmv max
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		0	0.01 vol%	0	0	2.0 vol%	0	<1.0%	Storage <4 vol%, EOR <2 vol%	<100 ppm	---	350 ppm	<1%	
H_2		0	0.8-2.0 vol%	0	0	1 vol%	0	<1.0%	<4 vol%	trace	trace	<3 vol%	<1%	
CO		0	300-4000 ppmv	0	0	400 ppmv	0		2000 ppm	<10 ppm	trace	4000 ppmv	5000 ppmv	1000 ppmv
H_2S	<20 ppmw	0	0.01-0.6 vol%	0	0	<0.01 vol%	0	<100 ppmw	200 ppm	trace	trace	<3.4 vol%	10-200 ppmv TBD	10-200 ppmv Max
SO_2		100 ppmv	0	5000 ppmv	100 ppmv	0	100 ppmv	50000 ppmv	100 ppm	<10 ppm	25000 ppmv	---	50000 ppmv	
NO		100 ppmv	0	100 ppmv	100 ppmv	0	100 ppmv							
NO_2									100 ppm	<50 ppm	2500 ppmv	---		
TOTAL Hydrocarbons	<5 vol%												<3%	5% Max
NH_3														
HCl														
HF														
HCN														
COS														
TOTAL Sulfur								<300 ppmw					10-200 ppmv	
C_2H_6								<1.0%					<1%	
C_6H_6														
C_2+										<100 ppm	---	<0.01 vol%		
C_3+								<1.0%					<1%	
volatile hydrocarbons														
TOTAL Inerts													<3%	
Hg														
Metals														
Particulate														
Glycol	46 ppbv													174 ppbv
MEA														
Selexol														
Delivery Pressure													2,220 psig	2,000 psia
Delivery Temperature													120F max	120 F Max

ATTACHMENT A - QGESS Literature Search Spreadsheet

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QGESS Literature Search Results

Type Application Misc	Operating Pipelines									MISC					
	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
	Currently Operated Pipelines Canyon Reef Carriers (OosterKamp Presentation 2008 R&D Foundation Polytec)	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 Jackson Dome (OosterKamp Presentation 2008 R&D Foundation Polytec)	Currently Operated Pipelines McElmo Dome (WorleyParsons paper, "CO_2 Specifications for Pipeline Transportation")	Currently Operated Pipelines Val Verde Basin (TX) Natural Gas (WorleyParsons paper, "CO_2 Specifications for Pipeline Transportation")	AEP Mountaineer CCS project	CO_2 Norway Compressor Specification (CO_2 Norway)	Canyon Reef Project Specification (Doctor and Palmer)	Dakota Gasification 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)
CO_2	85-98%	98.50%	96.8-97.4%	99.70%	95%	96%	98.7-99.4%	>98%	95%	99.5 vol%	99.5 wt%	>95.0 vol%	96 wt%	22-90 vol% (water free basis)	99.95 vol%
Water	50 ppm wt	240 ppm wt	120 ppm wt		240 ppm wt	20 ppm vol		218 ppm		245 ppm wt	Dew point <-5°C	No free water, dew point <-29°C	60 ppm wt	No free water	8 ppmv
N_2	5000 ppmv	13000 ppmv	9000 ppmv	3000 ppmv	<40000 ppmv	<300 ppm	trace		5000 ppmv	100 ppmv	4800 ppmv	<40000 ppmv	6000 ppm wt		40 ppmv
O_2		<10 ppm spec				<50 ppm				10 ppmv	<10 ppmv	<10 ppm wt	300 ppm wt		9 ppmv
Ar															20 ppmv
CH_4	2-15% C6H14	0.20%	1.70%		1-5%	0.70%	trace		5%				0.3 wt%	0-4 vol% (water-free basis)	30 ppmv
H_2															
CO						1000 ppm					<10 ppmv				2 ppmv
H_2S	<200 ppm	<20 ppm spec			0.002%	0.90%	trace		100 ppm			<1500 ppmv	1 wt%	10-77 vol% (water free basis)	0.5 ppmv
SO_2											<10 ppmv				2 ppmv
NO											<50 ppmv				2.5 ppmv
NO_2															2.5 ppmv
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
C_2+			0.3-0.6%		trace	2.30%									
C_3+															
volatile hydrocarbons														Some ethane and propane	20 ppmv
TOTAL Inerts															
Hg															
Metals															
Particulate															
Glycol															
MEA															
Selexol															
Delivery Pressure										1070 psig min					
Delivery Temperature										85 F Max					