CO_2 ENHANCED OIL RECOVERY: PROCESS DESIGN SAFETY OF CRITICAL PARAMETERS

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Carbon abatement technologies are known as Carbon Capture and Storage (CCS), in which the carbon in fossil fuels is captured (as CO_2) either pre-combustion or post-combustion and committed to long-term storage so that it is not emitted to the atmosphere and does not therefore contribute to global warming. One option for CO_2 storage is through the use of carbon dioxide in enhanced oil recovery (EOR) techniques. The aim of this paper is to describe the process of CO_2 EOR, and the role safety engineering input during the design, furthermore the paper presents the most important aspects regarding the safety parameters, which need to be taken into account during the design stage. It also discusses how Safety engineers have an important role to play throughout the CO_2 injection design. A key area that will be discussed is the potential of the combined Flammability, Detection and Toxicity Analysis through out the CO_2 EOR life field on the existing platform monitors and safety of personnel.

KEYWORDS: CO_2 injection, Safety, Carbon Capture and Storage, Enhanced Oil Recovery, Process Design Safety Parameter, Flammability, Detection, Toxicity

INTRODUCTION

In recent years, it has been recognised that the threat of climate change, due to the emission of greenhouse gases, particularly carbon dioxide (CO_2) is one of the key environmental concerns facing modern society. Although aspects of the science remain the subject of expert debate, there is broad consensus that climate change is occurring and this is reflected in both international and national initiatives. Most industrialised countries, including the UK, have signed up to international conventions and programmes, in particular the UN Framework Convention on Climate Change 1992 and the Kyoto Protocol 1997. CO_2 EOR can increase oil production by approximately 5–15% beyond what is typically achievable using conventional recovery methods (Tzimas et al., 2005), while facilitating the long-term storage of CO_2 in the oil reservoir. It does this by dissolving in the oil thereby reducing the oil's effective viscosity and making it more mobile. The movement of the CO_2 front within the reservoir can then sweep the oil to the production wells. Extraction of additional hydrocarbons also makes more space available for CO_2 storage in the long-term.

PROJECT DESCRIPTION

The use of CO_2 as EOR is the leading option for demonstrating CCS in the UK (DTI, 2004 and House of Commons, 2006), not only on cost grounds and existing experience in EOR offshore and CO_2 EOR onshore, but also because it is permitted under the current London Convention and the Oslo and Paris Convention (OSPAR). There are also well-established frameworks for regulating activities related to offshore oil and gas production.

The project has three main components:

- The generation of 'carbon free' electricity through the construction of a gas reformer and new turbines to run on hydrogen alongside an existing gas-fired power station;
- The manufacture of hydrogen – in order to supply the power station – by reforming North Sea gas and capturing the resulting carbon dioxide; and
- The transportation of the captured CO_2 via an existing offshore pipeline to offshore platform in the North Sea – and injection into the reservoir to enable the additional production of oil that is not currently recoverable.

While each of the component technologies is already proven, their proposed combination at this scale, in an integrated Decarbonised Fuels system is unique. Figure 1 shows how these different technologies combine to create the project concept.

In this project, natural gas from North Sea gas fields transmitted via the National Transmission System (NTS) and converted to hydrogen and CO_2 by a process known as pre-combustion decarbonisation. The vast majority of the CO_2 will be removed from the gas stream and the remaining hydrogen rich fuel will then be used to generate electricity in a specially modified gas turbine. The proposal for this part of the project is for the construction, of power station, of a combined cycle gas turbine (CCGT) power plant with an installed capacity of nominally 550 MWe generating nominally 475 MWe of carbon-free electricity; enough to power as many as a three quarters of a million homes in the UK.

The captured CO_2 will be compressed and dehydrated then transported by an existing pipeline to a gas terminal. Where it will undergo further compression to convert the CO_2 from the gas to the liquid phase. From there, the CO_2 will then be transported via another existing pipeline to offshore platform in the North Sea. Once at the platform, the CO_2 will be injected into the mature oil field reservoir under the seabed, thereby facilitating enhanced oil recovery (EOR).

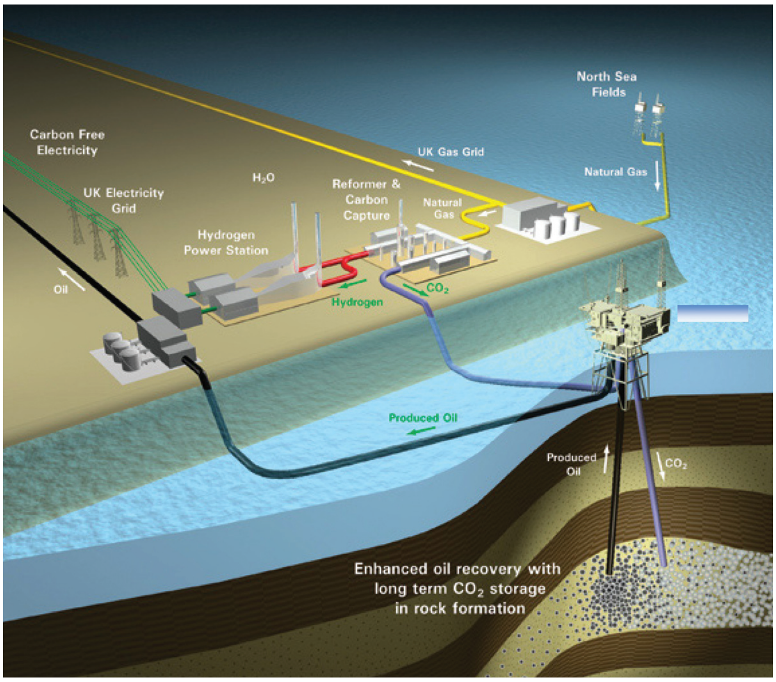

Figure 1. CO_2 enhanced oil recovery concept

CONCEPT SELECTION AND DESIGN

Initial concept selection for the project focussed on site selection for a suitable onshore power generation site. The onshore site appraisal exercise was undertaken within the context of a number of broad objectives of the project:

- To supply approximately 500 MW of power to the UK national grid generated from hydrogen rich fuel produced from existing North Sea gas supplies;
- To build a power plant at a location that is or can be served by existing North Sea gas supplies; and
- To build a power plant at a location that can export the CO_2 from the reformers to a depleted oil or gas field in the North Sea where it could be used for CO_2 EOR.

CO_2 TRANSMISSION

A number of engineering studies were undertaken to investigate available options for compression and transport of CO_2 and a number of options were screened. For the purposes of concept selection, the design criteria were required to dehydrate, compress and transport CO_2 from 1 barg at the beach to a maximum of 240 barg for reinjection at the platform. The option, which had the least environmental impacts as it utilises existing onshore and offshore pipelines, has been taken forward into detailed engineering design.

HAZARD MANAGEMENT AND SAFE PLATFORM DESIGN

The Hazard Management design process requires all disciplines to identify hazards and propose methods to reduce those hazards to a level of risk that is as low as reasonably practicable. Within this scope, hazard management has encompassed safety, environment and health and has resulted in a number of philosophies, which are strategic to the safety of the platform. Underpinning the hazard management process is the identification of hazards by multi-discipline reviews and the development of design philosophies to provide clear guidance to the design teams. Engaging all disciplines in this process has developed a thriving health, safety and environmental culture allowing the free exchange of ideas and concepts. During the development of the design, opportunities have been identified to eliminate hazards at source and deliver an inherently safer design. The Fire & Gas Detection and ESD systems are fundamental to the safe operation of the CO_2 EOR plant, working closely together with the client as a single team to develop the philosophies required to support this strategy. Hazard identification studies have been held at key stages of the design and Multi-discipline hazard identification studies conducted to identify and quantify the risk to the platform and personnel.

During the deign stage, the safety engineer played a key role in focusing the design team scrutiny on the options which were available to them to deliver an inherently safer design. The following are some of the safety issues, which have been carried out by the safety engineer.

FLAMMABILITY ANALYSIS

Flammability refers to the ability of a mixture of fuel and air to sustain combustion when ignited. Hydrocarbon molecules will react with oxygen (burn) if heated sufficiently, for instance by a spark or similar ignition source. Vapour/air mixtures are flammable only over a limited range of vapour concentrations. This range is defined by the lower and upper flammability limits. Mixtures outside this range are described as, respectively, too 'lean' or too 'rich' for ignition. The change in flammable range refers to the change in the difference between these two flammable limits. These limits are defined as follows;

LFL	The lower flammable limit (LFL) is the minimum concentration of vapour or gas in air below which propagation of flame does not occur on contact with a source of ignition. Below the LFL there is too little combustible fuel to sustain a flammable mixture.
UFL	The upper flammable limit (UFL) is the maximum concentration of vapour or gas in air above which propagation of flame does not occur on contact with a source of ignition. Above the UFL there is too little oxygen to sustain a flammable mixture.

The inert properties of water, CO_2 and nitrogen present in the streams were considered by the flammability analysis. Inert gases play no part in combustion reactions but absorb heat when present in a hydrocarbon/air mixture. For that reason, adding inerts to a mixture tends to reduce the spread between LFL and UFL until finally the mixture is no longer flammable.

The main objectives of the flammability analysis on the stream compositions were to gain a clear understanding of how the flammable range of mixtures containing multiple hydrocarbons and multiple inerts, such as carbon dioxide (CO_2), nitrogen (N_2) and water vapour vary with increasing CO_2. A flammability analysis would also enable conclusions to be drawn regarding the types of detectors required over the life of the field life and provide an indication of when these detectors will be required.

The flammability analysis generally showed a decrease in the flammable range of the gas compositions over field life due to increasing CO_2. It can be seen from Figure 2 that the CO_2 has the greatest effect on the higher pressure systems (Production Manifolds, Export Gas Compressor Outlet stream (Produced Gas stream), and the HP Separator Gas stream) as they contain a proportionately higher proportion of methane. A small change is observed in the flammable range of the MP and LP Separator gas streams over the life of the field.

The Fuel Gas stream maintains a presence in all levels of the platform and is flammable throughout the field life. This confirms the need for flammable gas detectors. Flammable gas detectors will also be needed for the MP and LP separator gas streams, as they remain flammable throughout the field life.

The HP Separator Gas stream, Export Gas Compressor stream and the manifolds show a gradual increase in CO_2 content over the field life. This observation confirms the need for CO_2 detectors.

GAS DETECTION ANALYSIS

The main objectives of the gas detection analysis were to determine the

- order of detection of the hazardous components (HC, CO_2, H_2S) in the process streams.
- requirements for gas detection based on the detection limits of the gas components in air as defined by the client and HSE guidelines.

The order of detection was required to determine the gas concentrations at first detected gas and also for evaluating the toxic properties of the gas at the point of detection.

The detection analysis also sought to clarify issues regarding the possibility of detecting H_2S by inference in low H_2S content streams

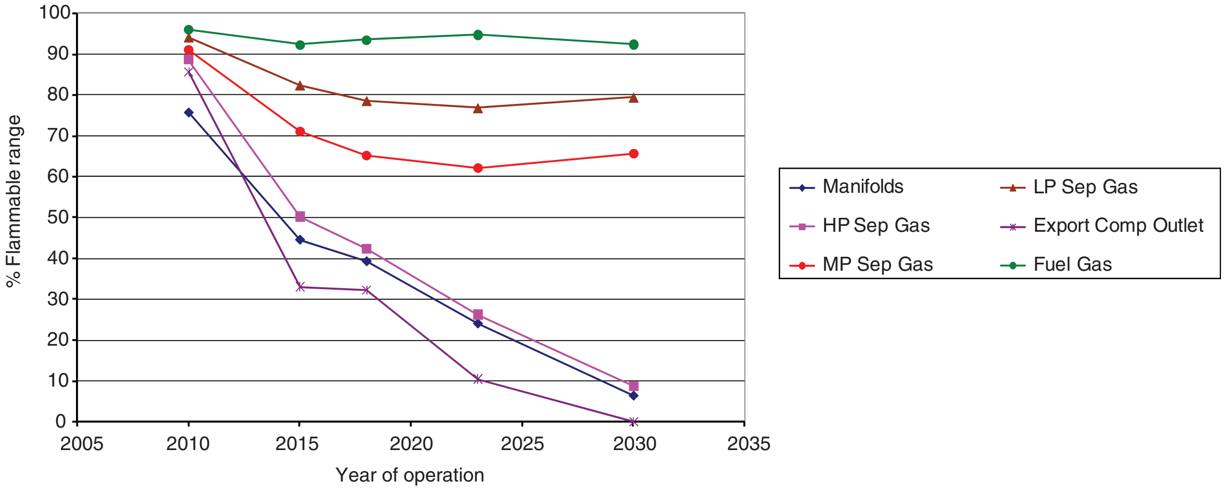

Figure 2. Variation of flammable range over field life

BASIS OF ANALYSIS

The gas detection analysis was carried out under the following assumptions

- Presence of all three gas detectors (HC, CO_2 and H_2S) at the source of release.
- Perfect mixing around the three detectors.

The Fire and Gas Detection Safety Philosophy for the platform is recommends the use of two types of infrared flammable gas detectors.

- Open Path Detectors
- Point Detectors

Open Path Detectors are most suitable for monitoring lighter hydrocarbon gas components and are recommended for general process area coverage in modules. Point Detectors are used for the monitoring of heavier, more toxic hydrocarbon gas components and are recommended for heavy gas monitoring around condensate pumps and in the wellbay of the platform. The analysis was thus based on these two types of infrared flammable gas detectors. The order of detection is the order in which the hazardous components (HC, CO_2 and H_2S) in the gas stream are detected. It is the order in which the individual gas components reach their low and high alarm levels. These low and high alarm levels are presented in Table 1.

OPEN PATH DETECTORS

Open-path detectors typically consist of a radiation source and a physically separate remote detector. The detector measures the average concentration of gas along the path of the beam. The unit of measurement is concentration multiplied by path length (% LEL × m or ppm × m). This makes it impossible to distinguish whether a reading is due to a high concentration along a small part of the beam or a lower concentration distributed over a longer length.

The open-path detector used for the analysis was the Dräger Polytron open path gas detector and the alarm levels used for the analysis was 1 LELm for low level alarm and 3 LELm for high level alarm in accordance with Fire and Gas Detection Safety Philosophy of the platform.

Infrared detectors are calibrated for the hydrocarbon gas they are least sensitive to. IR open path detectors operate at or around 2.1 μm (these are the most modern open path devices) and are least sensitive to propane gas. They are therefore calibrated for propane. The detector will alarm when the infrared light absorbed by the molecules of the hydrocarbon gas components equals the light absorbed by propane gas at the calibration concentration. The mechanism of detection is thus additive.

POINT DETECTORS

Point detectors operate by measuring the concentration of the gas at the sampling point of the instrument. The unit of measurement can be:

- % volume ratio;
- % lower flammable limit (LFL) for a flammable gas;
- ppm or mg/m^3 for low level concentrations (primarily used for toxic gases).

The analysis was based on the Simtronics GD10P IR point detectors. The alarm level assumed was 20% methane LEL for low level alarm and 60% methane LEL for high alarm level. These values are in accordance with the Fire and Gas Detection Safety Philosophy of the platform.

Point detectors are least sensitive to methane and are therefore calibrated to this gas. This ensures that any released process gas is not overestimated. The mechanism of operation of point detectors is also additive. Table 2, obtained courtesy of Groveley[4] Detection, gives the cross sensitivities of the Simtronics GD10P IR point detector to other hydrocarbon components.

The result for the produced gas stream (export compressor outlet stream), selected to represent the open path detection analysis and the result for the MP separator oil flash gas stream, selected to represent the point detection analysis are presented in this section as examples. The results present the detection profile of the areas covered by both flammable detector types. They are useful for evaluating the suitability of the detectors over the field life. The order of detection was determined at low and high level alarm for all streams in the process. The stream composition data used in the analysis was obtained from the Heat and Mass Balance Report and was based on the 2010 HP Ops data.

The determination of the order of detection enabled the gas concentrations in air at low and high-level alarm levels to be established. The gas concentrations in air at low and high level alarm levels are a prerequisite in evaluating the toxic properties of the gas at the point of detection. The results present the order of detection of selected streams for both open path and point flammable detectors, and the concentration of the detected gas components at the first detected gas.

Table 1. Low and high alarm levels

Gas component		Low level alarm	High level alarm
Hydrocarbons	Open path	1 LELm	3 LELm
	Point	20% LEL Methane	60% LEL Methane
CO_2		0.5% (5000 ppm)	1.5% (15,000 ppm)
H_2S		0.0005% (5 ppm)	0.001% (10 ppm)

Table 2. Simtronics[4] GD10P IR point detector sensitivities

Component	Sensitivity low level alarm (%LFL)	Sensitivity high level alarm (%LFL)
Methane	20	60
Ethane	12	36
Propane	4	12
i-Butane	5	15
n-Butane	5	15
i-Pentane	10	30
n-Pentane	10	30
n-Hexane	16	48

TOXICITY ANALYSIS

Toxicity is the degree to which a product can cause personal injury or illness when inhaled, swallowed, or absorbed through the skin. The increase in CO_2 content of the produced gas over the field life has the potential to significantly alter the toxic risk profile of the platform. It was thus necessary to investigate the properties of the toxic components in the process streams (HC, H_2S and CO_2) with a view to assessing the toxic potential of these components in the event of a loss of containment.

The toxicity analysis enabled an evaluation of the toxic properties of the released gas at low and high alarm levels. The assessment was useful in determining whether the concentrations of the detected gas at the low and high alarm levels are within the limits prescribed by the HSE workplace exposure limits[3].

Other objectives derived from the analysis include:

- the determination of the variation in toxicity of process streams over field life.
- the determination of the largest contributor to the toxicity amongst the individual components.

COMBINED TOXIC EFFECT MODEL

The combined toxic effect model is used to determine the gas concentration corresponding to a toxic load of 1. A toxic load of 1 represents the toxicity of a gas mixture that corresponds to the toxicity at the reference impairment level. The model considers the additive effects of all toxic components in the gas and could also be modified to account for the oxygen depletion effect (relevant for immediate impairment criteria only) of the gas thus predicting the overall gas concentration that leads to impairment. The combined toxic effect model is represented by the Equation (1) below.

$$\frac{C_1}{L_1}+\frac{C_2}{L_2}+\frac{C_3}{L_3}\cdots\cdots\cdots\cdots\frac{C_n}{L_n}=1 \qquad (1)$$

Where,

C = concentration of the toxic component in air

L = corresponding threshold limit of the toxic component (toxic component impairment criterion)

Oxygen depletion excluded (relevant for immediate fatality analysis only).

If the total dose exceeds unity, then the impairment level is deemed to be exceeded.

The minimum gas concentrations corresponding to a toxic load of 1 were determined using the model and were based on four impairment criteria. These impairment criteria values were sourced from the toxicity report. These values are listed in Table 3.

The results from the toxicity analysis are based on the 15 minute short term exposure limit (STEL) because of its relevance to the time frame for detection and escape. The toxic load corresponding to the short term exposure limit (STEL) is the total toxic load received over a 15 minute exposure duration. The results presented by the toxic load profile Figure 3 give the toxic load received over a 1 and 5 minute exposure duration, assuming a linear correlation of toxic load with time. It is assumed that the average time frame from the detection of a gas leak to the initiation of a response by the control room is about 5 minutes.

The toxic load profile Figure 3 for each stream show that the toxic load received in 5 minutes is more than the toxic load corresponding to STEL with the absence of an early warning system and the toxic load received in 5 minutes is less that the toxic load corresponding to STEL with the presence of an early warning system. The change in toxic load observed from Figure 3 over the field life is a result of the changing composition of toxic components within the stream. This observation justifies the need for an early warning system to facilitate a quick escape of personnel from the hazardous area at low level alarm. The results confirm that the current detection levels are appropriate for the monitoring of gas releases, subject to the implementation of an early warning system.

Figure 3 showing the contributions to the toxic load show that the largest contributors to the toxic load

Table 3. Impairment criteria values

	Impairment criteria (%)			
Component	Low level alarm (8 hour LTEL)	High level alarm (15 minutes STEL)	Escape	Immediate fatality
H_2S	0.0005	0.001	0.06	0.06
CO_2	0.5	1.5	5	10
Methane	0.1	0.15	0.45	30
Ethane	0.1	0.15	0.45	13
Propane	0.1	0.15	0.45	4.7
Butane	0.06	0.075	0.2	1.7
Propane	0.06	0.075	0.3	0.8
Hexane	0.002	0.05	0.3	0.3
O_2				13

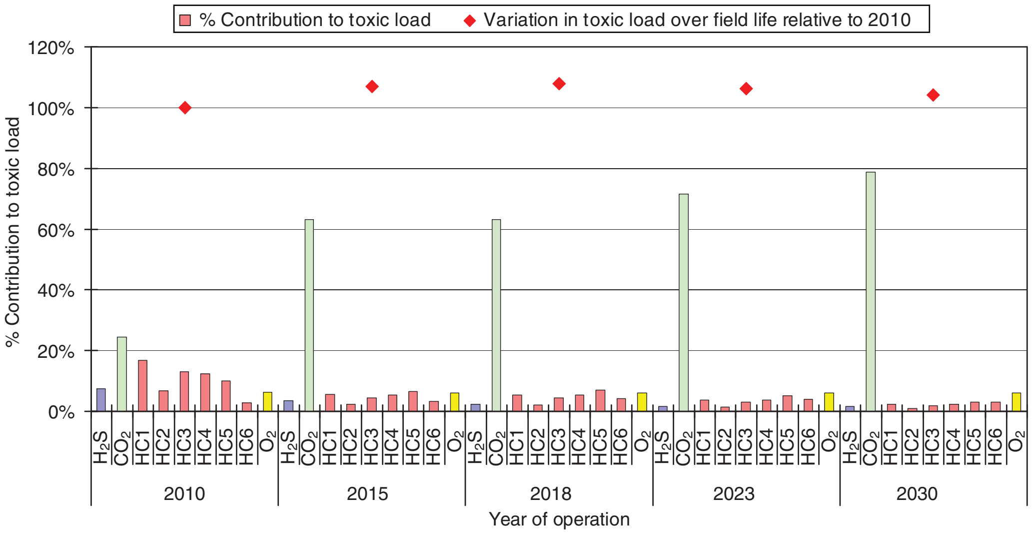

Figure 3. % Contribution of individual components to the toxic load corresponding the immediate impairment criteria and variation in toxic load over field life (produced gas stream)

corresponding to the short term exposure limit for all the selected streams are hydrocarbons. This observation holds true for most of the streams in the process based on the STEL criteria.

Figure 3 shows a steady increase in the contribution to the toxic load over field life by the CO_2. It also shows a decrease in the contribution to the toxic load by the hydrocarbons but shows the toxic load remaining fairly constant. This observation is explained by the increase in toxic load resulting from the CO_2 increase being offset by the toxic load reduction due to the decrease in hydrocarbon content. This trend is mirrored in all the streams with increasing CO_2 content.

The results from the toxicity analysis show that toxic hazards are generally unchanging over the field life (ignoring synergistic effects of hyperventilation due to CO_2 inhalation). This is contrary to the conclusions drawn from earlier studies into the effect of increasing CO_2 on the toxic hazards. Toxic hazards were generally expected to increase steadily over the field life due to increasing CO_2.

CONCLUSIONS

During the CO_2 EOR deign stage; the safety engineer played a key role in focusing the design team scrutiny on the options, which were available to them to deliver an inherently safer design.

The flammability analysis confirmed the need for hydrocarbon and CO_2 detectors in production manifolds, export gas compressor outlet stream, HP separator, MP and LP separator gas streams over the life of the field. This is due to the presence of both flammable and high CO_2 content streams in these modules.

Results from the detection analysis indicate the prevalence of hydrocarbons and CO_2 detectors over H_2S for both detector types over the life of the field. The analysis thus confirmed the need for hydrocarbon and CO_2 detectors. The analysis also presented the possibility of detecting H_2S by inference subject to a detailed analysis of the recovered flare gas and fuel gas reject CO_2 streams as well as the a few other hydrocarbon process streams and produced water streams with concerns regarding H_2S detection levels.

The toxicity analysis results confirm that toxic hazards are generally unchanging over the life of the field. This conclusion ignores synergistic effects of hyperventilation due to CO_2 inhalation. A study into this effect is recommended as a detailed design activity.

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