

CCS CO₂ RISK MANAGEMENT – NEW INDUSTRY GUIDANCE

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Carbon Capture, [Transportation, Injection] and Storage (CCS) projects will take many forms but they will all require the safe and responsible handling of a very large carbon dioxide (CO₂) stream that will likely need to be transported large distances over land, under the sea, and possibly on board ships before being injected deep underground.

CO₂ is a familiar and everyday substance but its behaviour and characteristics, particularly when being handled in large quantities in its liquid and supercritical phases, are not generally understood sufficiently to ensure its hazard potential is adequately managed. When concentrated, under pressure and in very large quantities a CCS CO₂ stream Loss Of Containment (LOC) event could result in a major accident hazard (MAH), the risks from which need to be effectively managed down to an acceptable level, just like any other potential MAH.

DNV has been active within the CCS field since around 2000 undertaking both internal and industry sponsored research and development. In August 2011 DNV initiated the CO₂ Risk Management (CO2RISKMAN) Joint Industry Project (JIP) to develop a publicly-available guidance document on MAH risk management of the CO₂ stream within a CCS project. Sixteen organisations (see Acknowledgements) joined the JIP to provide knowledge and guidance in the development of a relevant and comprehensive reference source for the emerging CCS industry.

A key aim of the JIP is to provide the CCS industry with guidance to help in the development of consistent, coherent and robust CO₂ MAH risk management. The guidance covers all the main links in the CCS chain and all lifecycle phases of the CO₂ system with particular focus on the concept development and operation phases.

The CO2RISKMAN guidance is scheduled to be released by the end of October 2012.

This paper introduces the guidance document, provides an overview of the challenges associated with effective MAH risk management of the CO₂ stream and highlights how the guidance will help projects resolve these challenges to deliver effective CO₂ MAH risk management.

1. INTRODUCTION

There is an urgent drive to implement CCS on a commercial and global scale. For success this needs to be done in a demonstrably safe and responsible manner that gains widespread acceptance of stakeholders, most notably regulators and the public.

Many aspects of CCS have been successfully deployed in various industries, however, scaling up and integrating the component parts of the CCS chain from capture to storage is new and therefore adds fresh challenges. The handling of tens of thousands of tonnes of CO₂ is also new outside the CO₂ Enhance Oil Recovery (EOR) industry in the United States.

CO₂ is a substance that has many everyday uses from carbonising drinks to decaffeinating coffee to chilling food. But CO₂, if it is inhaled in sufficiently high concentrations, can cause harm to people through toxicological impact and, at higher concentrations, by displacing the oxygen in the air to cause asphyxiation.

This hazardous aspect of CO₂ combined with the very large quantities that will be contained within CCS systems creates the potential that a leak from a CO₂ system could pose a MAH.

In addition, captured CO₂ will not be 100% pure, the CO₂ stream from capture plants will contain impurities such as CO, H₂O, H₂S, NO_x, SO_x, O₂ and H₂ that, although in

very low levels, can increase the likelihood and/or consequences of CO₂ system leaks.

The processes to manage the risks from hazardous operations are well tried and tested across many industries and these processes can, when appropriately applied, ensure that the CO₂ system risks are brought down to and subsequently maintained at an acceptable level.

A vast wealth of experience from other industries is available and is being integrated into the CCS industry and this is very valuable. However, such experience integration requires care as to ensure the specifics and peculiarities of CCS are adequately reflected going forward.

There will likely be a number of separate organisations delivering links in each CCS chain and it is important that knowledge transfer is delivered in a consistent and coherent manner for all parties to use.

For the hazard management of the CO₂ systems it is essential that the numerous discipline professionals, who together will be responsible for delivering a fully chain-integrated and low risk operation, gain an adequate understanding of the characteristics and behaviour of the CO₂ stream and the issues and challenges of handling it in very large quantities.

The CO2RISKMAN guidance (the Guidance) has been developed within a JIP, led by DNV, to provide CO₂ stream specific information and guidance for the CCS

industry to help ensure effective management of the CO₂ stream safety and environmental MAHs.

The Guidance should be completed by October 2012 (i.e. prior to the IChemE Hazards XXIII conference) and made available for free download from the www.DNV.com/ccs website.

The CO2RISKMAN guidance is complementary to DNV's other CCS industry initiatives that has seen the development of Recommended Practices and guidelines covering CO₂ capture, pipeline transportation, injection wells and geological storage (RP-J201 2010, RP-J202 2010 & RP-J203 2012).

2. CO2RISKMAN GUIDANCE

The CO2RISKMAN guidance is intended to assist CCS developers and operators build and implement an effective and coherent safety and environmental MAH risk management process for the CO₂ handling system across the various parts of the complete CO₂ system (i.e. links in the CCS chain).

The Guidance does this by providing background knowledge on MAH management, CCS and the characteristics and behaviour of CO₂. It also describes CO₂ stream-specific design and operation challenges and goes on to list generic potential LOC causes, escalation routes and consequences. As CCS projects will likely be developed and operated as separate links in an overall chain, the Guidance reflects this by then providing, in addition to the generic guidance, CCS link-specific hazard management guidance, information and examples of possible hazard management measures.

The Guidance should not be considered as prescriptive or all-encompassing but rather a comprehensive source of information that can be used to raise awareness of the issues, form a basis of discussion, and provide stimuli within the normal hazard management processes. It is intended for use by the various discipline professionals within a CCS project or operation to supplement their existing experience and knowledge with the CO₂ stream aspects.

The Guidance should also assist regulators in having effective and consistent regulatory interaction with CCS developers and operators. The Guidance can be used as a common reference.

In general, the Guidance should help promote improved engagement within and between CCS developers, between CCS developers and their regulators, and between the various stakeholders who have influence within the safe and sustainable implementation of CCS.

Figure 1 illustrates the pyramid structure of the Guidance. [Note: the Guidance is, at the time of writing this paper, still under final development and its structure may be refined before publication.]

The Guidance has a total number of pages of around 400 with the majority of these pages contained within the Levels 3 and 4 documents. Each Level of the Guidance will be contained within a separate document although Levels 1 and 2 may be combined into one physical document.

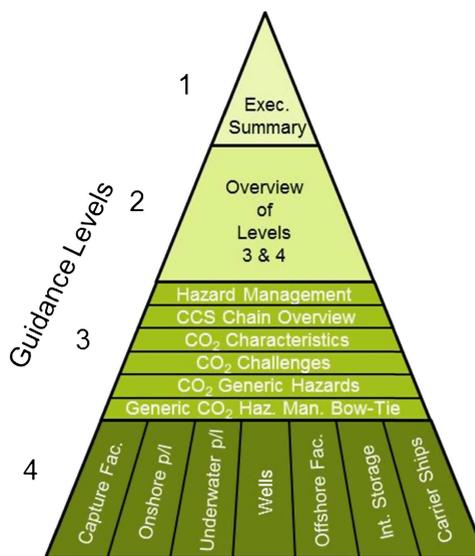


Figure 1. Guidance Pyramid Structure

It is intended that a user of the Guidance, depending on the need for information and time available, would progress through Levels 1 to 3 and possibly into project-relevant sections of Level 4. For example, a hazard management specialist concerned with the risks associated with operating an offshore CO₂ injection facility may skip through Levels 1 and 2, and the hazard management section of Level 3, and focus on the CO₂ specific sections of Level 3 and the sections of Level 4 that cover the Offshore Facility, Wells and Offshore Pipeline. Figure 2 illustrates the intended navigation through the Guidance.

Each CCS chain link covered in Level 4 is structured to provide information and guidance following the hazard management steps: Hazard Identification, Risk Assessment and Risk Treatment (using ISO 31000 terminology). The hazard

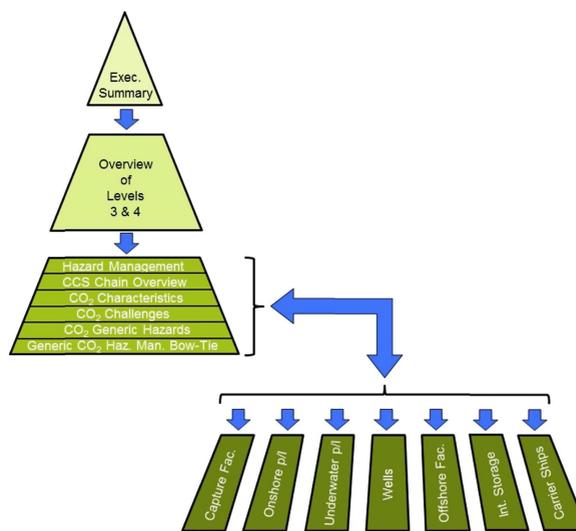


Figure 2. Guidance User Navigation

identification is based around the generic hazards introduced in Level 3 and examples of risk treatment measures are given for each hazard cause, consequence and escalation route broken down into Prevention, Detection, Alarm, Control, Mitigation and Emergency Response, reflecting the risk management hierarchy described in Level 3. It is expected that to get full value from the Guidance a hazard management specialist would use both Levels 3 and 4.

2.1 HAZARD MANAGEMENT

The number of organisations that could be involved in delivering an integrated CCS operation along with their unfamiliarity of the hazards associated with handling very large quantities of CO₂, adds to the challenge of ensuring major accident risks are effectively controlled.

The hazard management section of the Guidance's Level 3 provides an overview of generic risk management and its application within the context of effectively managing major accident risks within CCS. It does not attempt to provide a detailed and comprehensive guidance on MAH risk management as there is already a number of existing publications that adequately cover this. It should, however, provide a good introduction to the subject for those not familiar with MAH risk management.

Four of the key challenges associated with CCS hazard management are:

1. Complexity and scale of CCS projects and operations
2. Multi and cross-industry and regulator involvement
3. Lack of track record within industry and their regulators
4. Need to gain and maintain stakeholder acceptance

These challenges are compounded by:

- Lack of experience handling very large quantities of liquid and supercritical phase CO₂
- Absence of CCS-specific or CCS-validated reference material and tools
- Need to integrate hazard management across the whole CCS chain
- Lack of maturity in CCS personnel competency development
- Rapid technology development and innovation
- Trans geographic, legislative and national nature of CCS
- Political pressures (e.g. for rapid implementation, scale-up, cost reduction)
- High impact of an actual or perceived major event (e.g. a large leak from a CO₂ pipeline)
- Lack of stakeholder awareness and understanding

As noted above, different organisations are likely to be responsible for delivering and operating different parts of a CCS chain. These organisations will have their own corporate approaches to risk management, albeit all will be striving to ensure that the risks that are associated with their responsibility are managed down to an acceptable level. They will also have different tolerance and acceptance to risk, as well as different drivers (e.g. regulations). This needs to be recognised and harmonised as far as possible

across a CCS operation at the earliest opportunity. A holistic lifecycle approach to risk management should be a goal where resources can be focused on the most significant risk contributors throughout the CCS chain.

An added complication within CCS projects is that the management of some hazards will incorporate measures or actions taken in other parts of the CCS system, which will require effective communication and collaboration between organisations in order to holistically reduce risks across the whole CO₂ system or operation.

It is therefore essential for a CCS project or operation that the organisations responsible for delivering parts of the complete chain work closely together in a consistent and coherent way. The major accident risk management within and across a CCS project or operation needs to:

- Be based on principles, policies, objectives, risk acceptance criteria and key performance indicators that are aligned within the project to deliver effective holistic lifecycle major accident risk management
- Be based on consistent, best available knowledge, experience, base data and assumptions
- Use aligned hazard screening approaches
- Use aligned approaches and criteria within any cost benefit analysis of risk reduction measures
- Be carried out by suitably competent resources
- Have aligned reporting metrics, risk communication language and formats
- Follow a consistent and comprehensive stakeholder communication and consultation strategy that aims to foster an open, honest and constructive relationship with external parties (e.g. regulators, financial, underwriters, local government agencies and services, NGOs, adjacent businesses, public, etc.).

2.2 CCS CHAIN

The CCS chain is comprised of a number of integrated systems, which when linked together cover all processes from CO₂ capture, through to transport, injection and storage. Carbon capture may be included at the concept stage in new developments, or be retrofitted to existing facilities. A CCS system may comprise a single 'point-to-point' scheme, where a single capture source is linked directly to a single storage site. Alternatively, a CCS system may comprise of integrated 'networks', where shared or interconnected infrastructure is used to transport CO₂ from multiple sources to an individual or multiple injection sites.

A CCS chain will, in general, be comprised of some, potentially all, of the following components:

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- | | |
|--------------------------------------|--|
| ● CO ₂ Capture Facilities | ● CO ₂ Conditioning and Compression |
| ● Onshore & Offshore Pipelines | ● Intermediate Storage Facilities |
| ● Onshore & Offshore Injection | ● CO ₂ Carrier Ships & (Un)Loading Facilities |
| ● Storage Sites | ● Injection & Other Wells |
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Contained within Level 3 of the Guidance is an introduction to CCS and overview of each of the various links of a CCS chain.

To give an idea of capacity requirements for a CCS CO₂ handling system, for a relatively small 300 MWe power station with a single capture train and 90% capture efficiency, the CO₂ mass flow rate would be in the order of 95 tonnes/hour for a gas station and around 205 tonnes/hour for a coal station (ZEP, 2011). With larger power stations and if a number of CO₂ sources feed into a network transport system the mass flow within the network could rise to many thousands of tonnes per hour.

2.3 CO₂ CHARACTERISTICS

Carbon dioxide is a colourless, odourless gas, and at standard temperature and pressure (STP), it is about 1.5 times heavier than air.

CO₂ can exist as a gas, liquid, solid or a supercritical fluid (SCF). Under normal atmospheric pressures CO₂ can only exist as a gas or solid. CO₂ cannot exist as a liquid under atmospheric conditions. CO₂ sublimates directly between solid and gas across the sublimation line shown in CO₂ phase diagram in Figure 3. At a pressure and temperature above the critical point CO₂ exists as a supercritical fluid. In this region CO₂ possesses the viscosity similar to that of a gas and the density closer to that of a liquid.

CO₂ can be transported as a compressed gas but for economic and technical reasons, CO₂ captured for CCS application will predominantly be transported either in liquid/SCF conditions in pipelines or as a saturated liquid

in ship carriers. Typical transportation conditions for CO₂ are illustrated in Figure 3.

A phase diagram, as shown in Figure 3, is a common way of representing the phases of a substance and the conditions under which each phase exists. However, it tells us little regarding the change in the thermodynamic state of a substance during a transient event, for example, a leak to atmosphere or a system depressurisation. To understand the behaviour of CO₂ in a process or release to atmosphere, the Pressure-Enthalpy (P-h) diagram (sometimes called Mollier diagram) or the Temperature-Entropy (T-s) diagram can be used. Contained within Level 3 of the Guidance is a description of how the P-h or T-s diagrams can be used to predict the final conditions of a CO₂ system depressurisation or leak.

In humans, CO₂ is a normal component of blood gases at low concentrations, however if inhaled at high levels it can be lethal. Humans are very sensitive to changes in CO₂ concentrations. In addition to the hazard of asphyxiation due to CO₂ displacing oxygen in the air, the inhalation of elevated concentrations of CO₂ can increase the acidity of the blood triggering adverse effects on the respiratory, cardiovascular and central nervous systems. Depending on the CO₂ concentration inhaled and exposure duration, toxicological symptoms in humans range from headaches, increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma and death (EPA, 2000).

Breathing air with a CO₂ concentration of around 5% will within a few minutes cause headache, dizziness, increased blood pressure and uncomfortable and difficult breathing (dyspnea). At CO₂ concentrations greater than

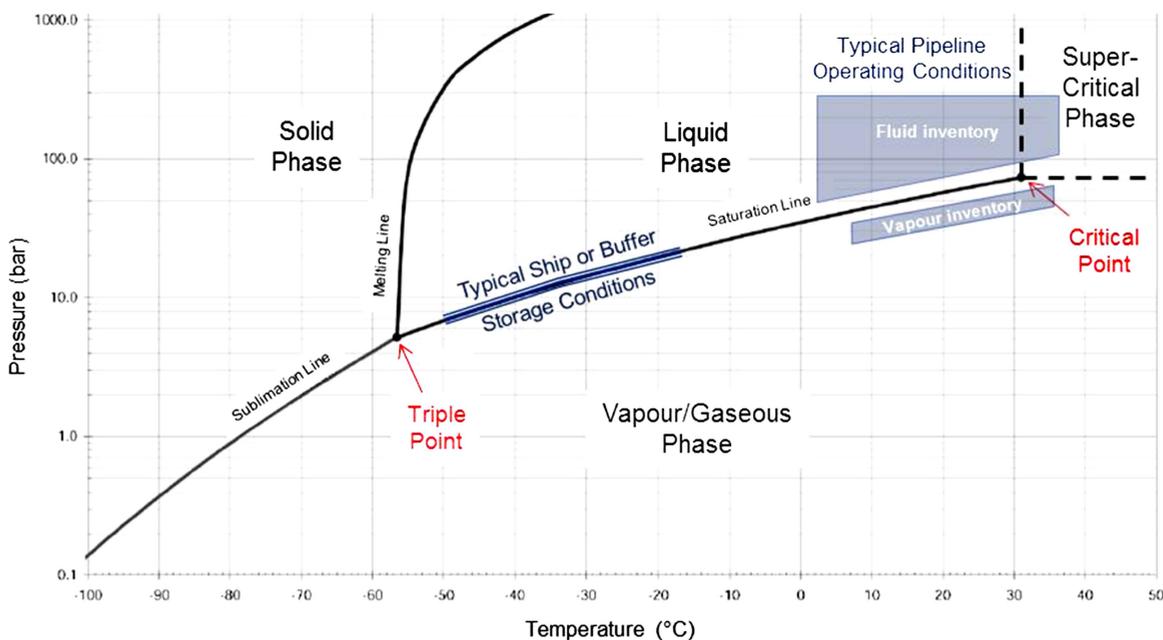


Figure 3. CO₂ Phase Diagram With Typical Transportation Conditions

17%, loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death occur within one minute of initial inhalation.

It should be noted that to pose an immediate threat to life from the toxicological impact requires a significantly lower CO₂ concentration than that to pose a similar threat due to oxygen reduction (i.e. due to asphyxiation). For example, a 20% rise in CO₂ concentration in air would reduce the O₂ concentration to around 17.5% which by itself would increase a person's pulse and breathing rate whereas as mentioned above, the toxicological impact would be immediately life threatening. Further details on the impact of CO₂ on humans can be found in the HSE's MAH human vulnerability guidance (HSE).

The dangers of breathing in elevated concentrations of CO₂ are well known to people such as divers, submariners, anaesthetists and astronauts (i.e. people who need to maintain inhaled gas mixtures within acceptable limits to sustain life). Outside these specialist communities knowledge about the impact of breathing elevated concentrations of CO₂ is generally low. Concentrated CO₂ inventories may be present, for example as part of a fire suppression system, but the potential for persons to be exposed to CO₂ inhalation are usually localised and the associated safety risks can be effectively managed through localised hazard management measures.

With the advent of CCS, where pipeline systems are likely to have inventories of liquid phase CO₂ in the order of 10s if not 100s of thousands of tonnes, the potential for widespread exposure to air with hazardous concentrations of CO₂ will exist.

To effectively manage the risks associated with handling large quantities of CO₂, a full understanding of the impact CO₂ has on the human body is required. Level 3 of the Guidance provides details of this.

The venting of liquid CO₂ to atmosphere whether through a vent or leak will result in a phase change as the CO₂ depressurises through the release aperture with vapour and solid CO₂ being formed. Anyone caught in the cold jet of gas with potentially entrained solid CO₂ particles will suffer cryogenic burns. Inhalation of such a cold atmosphere would also cause severe internal injuries.

Liquid and particularly supercritical phase CO₂ is a very efficient solvent. When there is substantial reduction in pressure of CO₂ in either of these phases, for example during a leak, it will change state to vapour phase essentially losing its solvency capacity, thus liberating any impurities within the stream which were previously held in suspension. This can lead to a build-up of impurities at the release point.

2.4 CO₂ HAZARD MANAGEMENT CHALLENGES

The following provides an overview of significant challenges that need to be considered within the MAH risk management process applied to the CO₂ handling system within a CCS project. Details on each can be found in Level 3 of the Guidance.

Inadequate Appreciation of CO₂ Hazards: Those responsible for, or have influence over, safety risk management need to have an adequate understanding of the potential hazard that CO₂ and the associated CO₂ stream impurities can pose within the CCS context and scale of operations. Without this there is potential for the CO₂ stream hazards to be inappropriately assessed and managed which could lead to increased risk levels and/or an overly high aggregate risk management cost burden on a project.

Mixture Phase Diagrams: The phase diagram of pure CO₂ is well known but the presence of impurities within the CO₂ stream such as H₂ or N₂ can result in significant changes to the phase envelopes. Models used for process and release modelling need to be able to predict the phase envelopes for the range of mixtures likely to be delivered from the various capture technologies using suitable Equations Of State (EOS). The shortcomings of the existing equations of state need to be understood, so that they can be incorporated into design. Experimental work is currently on-going to collect data for EOS refinement and validation but the range of impurity mixtures is large and as capture technology develops the impurity levels will likely evolve.

Material Compatibility: Liquid phase CO₂ and particularly supercritical CO₂, is commonly used as an industrial solvent. CO₂ can break down some lubricants either removing it or causing changes to its properties. This can lead to seizing or jamming of equipment (e.g. valves, pigs, non-return valves, etc.), damage to rotating equipment potentially leading to a significant loss of containment event, and contamination of the CO₂. In addition to its solvent properties, CO₂ is also highly invasive and capable of dissolving into materials and causing damage to the material particularly upon depressurisation. Seal elastomers are known to be vulnerable to explosive decompression damage, particularly when exposed to supercritical CO₂. This property means that careful selection of materials is very important for seals, flexible hoses, instruments, wire and cable insulators, controls and other safety-critical components

Internal Corrosion: CO₂ in combination with free water is well known (e.g. in the oil and gas industry) to form carbonic acid which is highly corrosive to carbon steels. The presence of impurities within the CO₂ stream may significantly heighten the corrosion rate by forming other acids (e.g. sulphuric, nitric, etc.) and changing water solubility properties. Developing a suitable CO₂ stream specification that will avoid impurity levels that could lead to unacceptable internal corrosion and then ensuring that there are no excursions outside this specification is extremely important.

Low Temperatures and Solid CO₂ Formation: Liquid or supercritical phase CO₂ when depressurised may, depending on the initial pressure and temperature conditions and final conditions, change phase to be a pure vapour, a two phase liquid and vapour mixture, a two phase solid and vapour mixture, or if the final conditions are at the triple point, be three phases solid, liquid and vapour. CO₂ cannot exist at atmospheric pressure in its

liquid phase. The depressurisation of CO₂ by design or by accident can result in temperatures within systems and/or within any release at or below, -78°C, the sublimation temperature of solid CO₂. In addition, significant quantities of solid CO₂ can be formed within systems and/or within any release which in addition to its low temperature could cause blockages, and subsequent hazard. Understanding the thermodynamics of the CO₂ stream, including the effects of the impurities, is of vital importance within the design and operation of CO₂ stream handling systems.

Thermal Expansion: CO₂ density is sensitive to temperature changes especially close to critical point conditions. This can result in system over pressurisation should an isolated (i.e. contained) inventory of liquid phase CO₂ increase in temperature due to, for example, heat radiation from the sun or flame impingement from an adjacent fire event.

Toxic Substance Deposits: As previously mentioned, liquid phase CO₂ and particularly supercritical CO₂, is a highly efficient solvent. During a release (e.g. venting or leak), the significant pressure reduction that occurs at the leak point changes the CO₂ from a super solvent to a vapour with virtually no solvent capability. Any impurity within the CO₂ stream that is dissolved by the CO₂ and held in solution will therefore be released should the CO₂ change phase to a vapour (e.g. at a release point). Any solid impurities that are released in this way could lead to a concentrated deposit of the substance at the release point, potentially causing harm to people or the environment over an extended period of time.

Propagating Pipeline Cracks: Fracture propagation and arrest in high pressure pipelines has been the subject of study for many years, there is, however, only limited experience with CO₂ pipelines. Should a pipeline propagating fracture occur, the contents of a pipeline can be released within a very short period. There are two fracture failure mechanisms, namely, brittle and ductile, and both can result in pipelines unzipping very rapidly along a considerable distance (e.g. hundreds or thousands of meters).

In brittle failures, following the crack initiation, the crack propagation is close to the speed of sound in the metal (400+ m/s). Aspects of a liquid phase CO₂ release that may lead to low temperature embrittlement are due to the Joule-Thomson effect and the formation of solid CO₂ at -78°C at a leak point, and within the pipeline due to the temperature reduction of the liquid CO₂ caused by the boil-off to sustain a pressure drop (e.g. due to a leak or venting) and from solid CO₂ deposits at pipeline low points should the pipeline pressure fall below 5.18 bara (i.e. triple point pressure) before all the liquid has vaporised.

In ductile failures, following the crack initiation, the crack will start propagating along the pipe. A race will occur between the crack propagation velocity and the speed at which the pipeline depressurises through the growing rupture. The crack will continue to propagate with a speed that is much slower than for a brittle fracture until either the depressurisation front overtakes the crack tip or the crack is stopped or slowed by a feature of the

pipe that increases its toughness. Due to the phase change that occurs at the release point of a CO₂ pipeline, the depressurisation front may travel at a relatively slow speed.

The approaches and methods to prevent crack propagation in CO₂ stream pipelines are known but the current uncertainty may result in overly conservative designs which could add a significant cost burden to a project.

CO₂ BLEVE: Boiling Liquid Expanding Vapour Explosion (BLEVE) is a very unusual but extremely catastrophic event. The principle behind a CO₂ BLEVE is that a very sudden depressurisation of a pressurised liquid such as CO₂ creates a superheated liquid phase that suddenly vaporises in an explosive manner. This may give a transient overpressure peak inside the vessel, which again may lead to a powerful burst of the whole vessel, with total loss of content, a resulting blast wave and risk of flying fragments. There have been some reported BLEVEs with CO₂, mostly involving fire extinguishers. In an accident involving a rupture of a 30 tonne capacity CO₂ tank that occurred in 1988 at a plant in Worms, Germany (Clayton, 1994), based on the damage, number and location of fragments, fatalities and injuries it was speculated that the failure caused a cold CO₂ BLEVE. For a CO₂ BLEVE to occur in a vessel it is believed that the CO₂ inventory must be within a defined BLEVE envelope, details of which are given in Level 3 of the Guidance. The effect of impurities on the BLEVE potential adds uncertainty to this potential hazard.

Toxic Effects of Pure CO₂: As previously mentioned CO₂ is a colourless and odourless substance that is a gas at atmospheric conditions and is naturally present in the air at a concentration of around 0.04% by volume. A release from a CCS CO₂ handling system will be of highly concentrated CO₂ (i.e. >95% CO₂ by volume) and until the release dilutes to a concentration of less than around 7% it will pose a significant and immediate threat to people who may inhale it. CO₂ is a heavier than air gas and as such a release will tend to slump and accumulate or be influenced by natural or manmade topographical features such as drains, valleys, basements, low lying ground. To create a hazardous CO₂ cloud of sufficient size and duration to pose a major accident threat would likely require a large and prolonged CO₂ release. Liquid phase CO₂ pipelines will contain tens and sometimes hundreds of thousands of tonnes of CO₂ which, if containment is lost, could foreseeably create a CO₂-rich cloud that could potentially threaten large geographical areas. The size of the visible cloud should not be used as an indication of the CO₂ concentration within the cloud. A large low momentum slumping CO₂ release that could accumulate in low lying ground may quickly become invisible as the water vapour cloud disappears as the cloud is warmed by its surroundings.

Toxic Effects of CO₂ Mixtures: The presence of impurities in a CO₂ stream may affect the potential inhalation impacts of a CO₂ stream release. Some incidental substances are toxic, such as CO, NO₂, SO₂ and H₂S, and it is important to understand the impact of possible impurities, both in isolation and combined with CO₂ and other impurities. In the event of a well blow-out that releases flow from

the well bore, the release may also contain down-hole formation solids, fluids and gases, such as hydrocarbons, H₂S and trace components of heavy metals. The possible constituents in a formation release will need to be considered.

Release Modelling: There is extensive experience modelling vapour phase CO₂ releases and current modelling tools and approaches should be adequate to assess the hazard potential from a CCS-scale vapour phase CO₂ inventory. The modelling of liquid and SCF phase CO₂ releases is, however, in its infancy and this raises the level of uncertainty within hazard assessment. The main challenge associated with modelling these phases of CO₂ is the potential for the formation of two phase, solid and vapour, flow. Release and dispersion models usually have the capability to model two phase liquid and vapour flow but CO₂ introduces the potential for solid and vapour flow which needs to be taken into account.

It is not only the selection of suitable modelling tools that is important but also the selection of the modellers who need to have sufficient competency in liquid and SCF phase CO₂ modelling. There are several gaps and uncertainties with respect to CO₂ modelling that need to be recognised and considered when scoping and undertaking CO₂ release modelling and when making use of the modelling output. These include (with details contained with the Guidance's Level 3) modelling of:

- Pipeline depressurisation
- Vessel depressurisation
- Buried pipeline release
- Subsea pipeline release
- CO₂ mixtures
- Confined release
- Release geometry
- Temperature envelopes
- Visibility
- Vertical/angled releases
- Low wind conditions

System Vents: The preceding discussion highlights the issues within a liquid phase CO₂ system when it is depressurised, however there also exists challenges associated with designing the depressurisation system itself (i.e. the vent system). In addition to the system having to be able to handle the cold temperatures and solid CO₂ formation that it may be exposed to, the release point must also be designed and located such that people are not exposed to harmful concentrations of CO₂ during all reasonably foreseeable conditions. Particular consideration must be taken when releasing a CO₂-rich stream in still weather conditions, especially if there is a temperature inversion, since the cold CO₂ stream being released may slump towards the ground or water surface with relatively low dispersion rates.

2.5 CO₂ STREAM GENERIC HAZARDS

Level 3 of the Guidance also provides information that can be used to assist in the hazard identification of CCS CO₂ handling system MAHs. It lists, along with relevant comments,

potential initiating causes that could lead to loss of containment events, potential immediate and delayed escalation, and potential consequences. It focuses on the CO₂ stream aspects and therefore does not seek to address non-CO₂ aspects which should already be understood by competent individuals coming into CCS from other industries or fields.

The lists of potential causes, escalation routes and consequences are not credited as being comprehensive and all-encompassing, rather they are included in the Guidance to stimulate thinking and discussion within normal CCS project hazard identification and assessment processes.

Included within Level 3 CO₂ Generic Hazards section are details on the following:

Potential LOC causes:

- Inappropriate human input or action during the design, operation, maintenance, intervention, etc., due to a lack of relevant CO₂ competency and/or experience
- Low temperature embrittlement of containment envelope due to rapid depressurisation of a liquid phase CO₂ inventory
- Low temperature embrittlement of containment envelope due to CO₂ stream flow expansion through valve, flow restrictor, etc.
- Internal corrosion due to out of specification impurities levels (e.g. water) entering system
- Internal corrosion due to maintenance or operation activities (e.g. pigging) allowing water to enter the system
- Internal corrosion due to melting of hydrate formation in stagnant line (i.e. no flow)
- Component failure due to inappropriate specification, selection or replacement of materials or operating outside material specification
- Overpressure from thermal expansion of a trapped liquid phase inventory
- Overpressurise due to vent or relief line blockage
- Overpressure due to rapid sublimation of solid CO₂
- Failure of supports due to change of pipeline/pipework use
- Mechanical failure or seizing due to inappropriate specification, selection or replacement of lubricants
- Loss of containment associated with use of a temporary equipment (e.g. 3rd party equipment)
- Loss of containment due to fluid hammer created by rapid closure of a valve.

Potential escalation:

- Propagating crack
- Leak enlargement (possible rupture) from low temperature embrittlement due to leak impingement (e.g. within a crater or congested area)
- Loss of containment of adjacent inventories and/or structures due to low temperature embrittlement from cold jet impingement, energy release, projectiles, etc.
- External corrosion due to small (pin-hole) leak acidifying water trapped close to the pipe

- CO₂ BLEVE of vessel
- Road traffic accident due to lack of visibility caused by water vapour cloud
- Exposure to a build-up of toxic and/or harmful substances at location of release
- Engulfment of helicopter during flight stage at offshore platform causing a crash.

Potential Consequences:

- Inhalation of elevated CO₂ concentrations in air
- Inhalation of hazardous levels of CO₂ stream impurities
- Inhalation of, or exposure to, very cold air mixture
- Contact with solid CO₂ or cooled surfaces
- Rapid expansion
- Projectiles
- Lack of visibility
- Loss of structural integrity due to low temperature embrittlement.

2.6 GENERIC BOW-TIE DIAGRAM

To graphically illustrate the potential causes, escalation routes and consequences associated with loss of containment events from the CO₂ stream across the CCS chain, a generic bow-tie diagram has been developed and is contained within Level 3 of the Guidance. This bow-tie diagram will provide a useful visual reminder of the CO₂ stream hazard management aspects for CCS projects as they undertake their hazard management processes.

2.7 CCS LINK-SPECIFIC GUIDANCE

The previous sections of this paper provide an overview of some of the detailed information contained within Level 3 of the Guidance. Level 4 builds on this generic information and provides pertinent information and guidance on hazard identification, risk assessment and risk treatment with regard to the CO₂ stream aspects for each link in the CCS chain separately.

Each section of Level 4 covers a link in the CCS chain. A systematic approach is taken to consider the challenges and generic hazards described in Level 3 and provide pertinent information and examples relevant to the CCS chain being considered.

For each potential CO₂ stream loss of containment cause, escalation route and consequence, a comprehensive list is given of measures that could be considered within a MAH risk management process, sub-divided into measures for prevention, detection, alarm, control, mitigation and emergency response.

Also included for each link of the CCS chain is discussion on the main cross-chain integration aspects. This is to highlight key areas where hazard management in one link of the chain has a dependency with another part or parts of the chain to deliver effective hazard management.

The risk management measures listed in each Level 4 section are not intended to be prescriptive, complete, or always relevant to all parts of the CCS link being con-

sidered, but they should provide stimuli to help the required discussions and debate within CCS projects that are key in the pursuit for an effective and balanced hazard management strategy at reasonable cost.

3. CONCLUSIONS

The DNV led CO2RISKMAN JIP will (in October 2012) publish a comprehensive and robust industry guidance document for the emerging CCS industry to help CCS projects and operations develop and implement robust strategies for addressing the challenges described in the early sections to deliver effective major accident hazard management for the CO₂ stream.

The Guidance is structured into four Levels to allow it to be used to inform, educate and provide guidance to various levels of a CCS project or operation from management to hazard management specialist. The Guidance is not prescriptive, its goal is to help projects develop their own integrated hazard management strategy that adequately includes and addresses the 'new' aspects brought in by the need to handle very large quantities of impure CO₂.

A CCS project that adopts the Guidance as a common reference source across all the links of the chain should find it easier to implement a consistent, coherent and full-chain approach to major accident hazard management. The project should also find it easier to communicate hazard management aspects amongst the various organisations within the CCS chain and with external stakeholders such as their HSE regulator.

There is no reason why handling the very large quantities of CO₂ that will be required to make CCS an effective part of global carbon reduction cannot be performed in a safe and responsible manner. In fact, the CCS industry, which is starting from a relatively clean piece of paper, has a huge opportunity to build on the knowledge, experience and lessons of other industries to develop fit-for-purpose, effective, major accident hazard management approaches and standards aimed at delivering high levels of safety performance at reasonable cost.

The CO2RISKMAN Guidance is intended to assist the CCS industry in this goal.

The Guidance will be available for free download from www.dnv.com/ccs.

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REFERENCES

- Clayton, W.E., and Griffin, M.L., Catastrophic Failure of a Liquid Carbon Dioxide Storage Vessel, *Process Safety Progress*, 13, 1994: pp.202–209
- RP-J201, 2010, Qualification Procedures for CO₂ Capture Technology, www.dnv.com/ccs
- RP-J202, 2010, Design and Operation of CO₂ Pipelines, www.dnv.com/ccs
- RP-J203, 2012, Geological Storage of Carbon Dioxide, www.dnv.com/ccs
- EPA (US Environmental Protection Agency), 2000, Carbon Dioxide as a Fire Suppressant: Examining the Risks, EPA430-R-00-002, <http://www.epa.gov/ozone/snap/fire/co2/co2report.pdf>
- HSE (UK Health and Safety Executive), Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment, <http://www.hse.gov.uk/foi/internalops/hid/spc/spctosd30-annex.pdf>
- ZEP (Zero Emissions Platform), 2011, The cost of CO₂ Capture, Post-demonstration CCS in the EU, p12.