Managing the Major Accident Potential of Carbon Capture and Storage CO_2

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"*When concentrated, under pressure and in very large quantities, a Carbon Capture and Storage (CCS) CO_2 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*."

This statement was a key message in a DNV paper presented nine years ago at the Hazards XXIII conference that raised awareness of a new industry guidance on CCS CO_2 MAH risk management – the CO2RISKMAN guidance.

Whilst the contents of this guidance remain as valid today as it did in 2012, what has changed over the intervening years is the exponential growth in CCS across the globe to support the drive for rapid, widescale decarbonisation. The consequence of this is that many CCS CO_2 system developers, operators and regulators, people who have influence on controlling the associated MAH risks, may have a lack of understanding of the properties and characteristics of CO_2 and how these can lead to, or result in, major accidents.

Commercial CCS projects will handle very large quantities of CO_2 with inventories of tens of thousands of tonnes. A significant CO_2 leak from one of these large inventories could result in widespread loss of life and, on a more strategic level, cause negative public perception and acceptance concerns for CCS implementation. Of particular concern are buffer storage and pipelines containing liquid phase CO_2 located onshore, in shipping ports, or near-shore as these will have the combination of large CO_2 inventory phase change issues should a leak occur, and likely proximity to the public or industrial sites.

It is vital that those responsible for promoting, implementing and regulating CCS are fully aware of the MAH potential associated with large inventory CO_2 containment systems so that they can be located, designed, operated and maintained to reduce the risks to people (and industry) to an acceptably low level.

This paper raises awareness of the properties and behaviours of CCS CO_2 and highlights how they could cause or contribute to a MAH event. It will reference the CO2RISKMAN Guidance and other industry standards and guidelines so that those who need additional knowledge know the references available and where to find them.

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 relatively new as is the handling of tens of thousands of tonnes of CO_2.

CO_2 is a substance that has many everyday uses from carbonising drinks to decaffeinating coffee and chilling food, but CO_2 if it is inhaled in concentrations above around 5% v/v in air will cause harm to people through toxicological impact with death probable when inhaled at around 17% v/v and above. It is a commonly held view that the threat to people from CO_2 is through asphyxiation when it reduces the oxygen level by displacement, however it is the toxicological harm that occurs at lower CO_2 concentration that creates a much greater hazard.

The very large CO_2 system flowrates and inventories of a CCS development combined with toxicological harm at concentrations noted above result in potential for a leak from a CCS CO_2 system rapidly forming a large scale, life-threatening cloud (i.e. causing a major accident event).

In addition, captured CO_2 will not be 100% pure, the CO_2 stream from capture plants will contain impurities such as CO, H_2O, H_2S, NO_x, SO_x, O_2 and H_2 that, although in very low levels, can increase the likelihood and/or consequences of CO_2 system leaks.

Major accident hazard risk management processes are well established and embedded within many industries and these processes can, when appropriately applied, ensure that the CCS CO_2 system risks are brought down and maintained at an acceptable level.

A vast wealth of experience from other industries is available and is being integrated into the CCS industry, however, such experience integration requires care as to ensure the specifics and peculiarities of CO_2 and 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 3 all parties to use.

For the hazard management of the CO_2 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 CO_2 stream and the issues and challenges of handling it in very large quantities. It should also be recognised that the management of a hazard in a downstream link of the CCS chain will depend on control measures being rigorously implemented in an upstream link, therefore effective communication and cooperation between the CCS component parts is essential.

The CO2RISKMAN guidance was developed by DNV within a Joint Industry Project (JIP) with sixteen other organisations to provide CO_2 stream-specific information and guidance for the CCS industry to help ensure effective management of the CO_2 stream safety and environmental MAHs. The CO2RISKMAN guidance was first released in 2013 with a further revision in 2020 to incorporate minor changes. It is available for free download from the www.dnv.com/ccus website.

2. CCS CHAIN

The CCS chain is comprised of a number of integrated systems, which when linked together cover all processes from CO_2 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 CO_2 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:

- CO_2 Capture Facilities
- Onshore & Offshore Pipelines
- Onshore & Offshore Injection
- Storage Sites
- CO_2 Conditioning and Compression
- Intermediate Storage Facilities
- CO_2 Carrier Ships & (Un)Loading Facilities
- Injection & Other Wells

To give an idea of scale for a CCS CO_2 handling system, for a relatively small 300MWe power station with a single capture train and 90% capture efficiency, the CO_2 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 CO_2 sources feed into a network transport system the mass flow within the network could rise to many thousands of tonnes per hour. With regard to CO_2 inventories, a 100km 90cm diameter pipeline if containing vapour phase CO_2 would have around 5,000 tonnes of inventory whereas the same pipeline if containing liquid phase CO_2 the inventory would be around 60,000 tonnes.

3. CO_2 CHARACTERISTICS

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

CO_2 can exist as a gas, liquid, solid or a supercritical fluid (SCF) depending on its temperature and pressure (see phase diagram in Figure 1). Under normal atmospheric pressures CO_2 can only exist as a gas or solid. CO_2 cannot exist as a liquid under atmospheric conditions and therefore leak from a liquid CO_2 pipeline will not flow or jet out as a liquid to potentially form a spreading pool of CO_2 – this is physically impossible. A liquid CO_2 leak will depending on inventory pressure and temperature, either be emitted as a gas-only release or a gas/solid CO_2 mixture with the solid CO_2 particles then subliming to a gas with heat energy drawn from the surrounding environment. At a pressure and temperature above the critical point CO_2 exists as a supercritical fluid. In this region CO_2 possesses the viscosity similar to that of a gas and the density closer to that of a liquid.

CO_2 can be transported as a compressed gas but for economic and technical reasons, there may be a preference for transporting it in liquid or SCF conditions in pipelines or as a saturated liquid in ship carriers. Typical transportation conditions for CO_2 are illustrated in Figure 1.

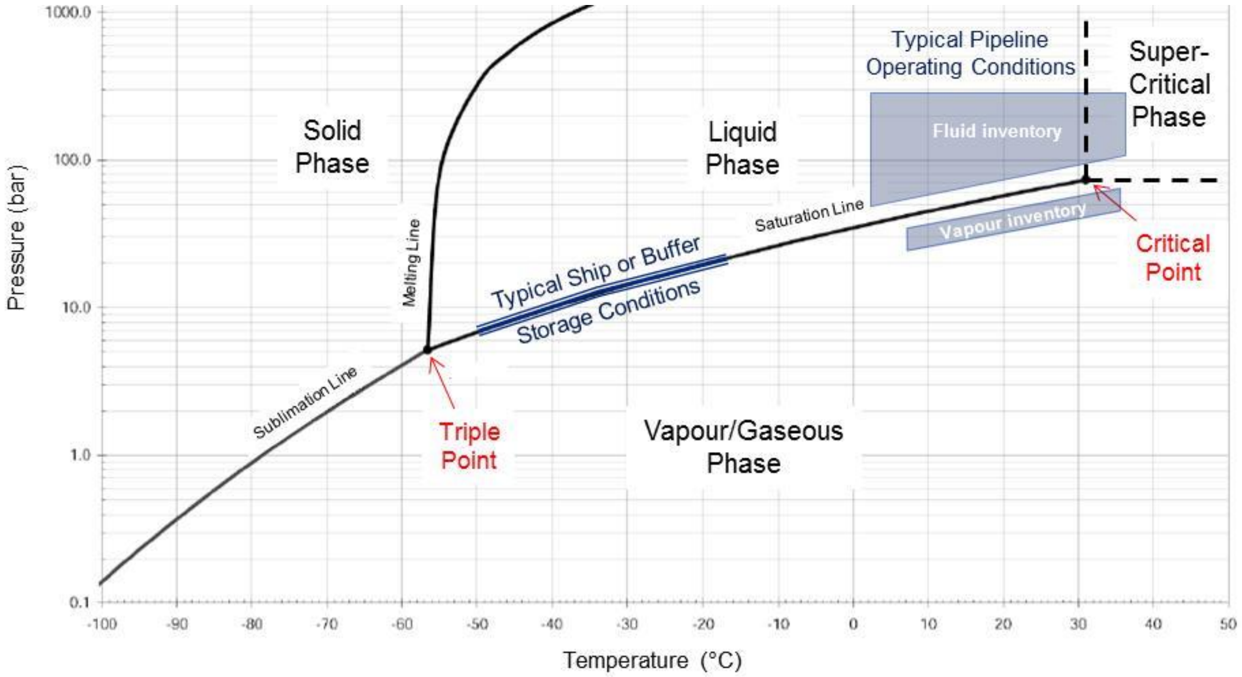

Figure 1. CO_2 Phase Diagram With Typical Transportation Conditions

A phase diagram, as shown in Figure 1, 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 planned system depressurisation. To understand the behaviour of CO_2 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 the CO2RISKMAN guidance is a description of how the P-h or T-s diagrams can be used to predict the final conditions of a CO_2 system depressurisation or leak.

In humans, CO_2 is a normal component of blood gases at low concentrations, however if inhaled at higher levels it can be lethal. Humans are very sensitive to changes in CO_2 concentrations and the inhalation of elevated concentrations of CO_2 above around 5% v/v in an air mixture can increase the acidity of the blood, triggering hyperventilation and adverse effects on the respiratory, cardiovascular and central nervous system. Depending on the CO_2 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 CO_2 concentration of around 5% v/v will within a few minutes cause headache, dizziness, increased blood pressure and uncomfortable and difficult breathing (dyspnea). At CO_2 concentrations greater than around 17% v/v, 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 CO_2 concentration than that to pose a similar threat due to oxygen reduction (i.e. due to asphyxiation). For example, a 20% rise in CO_2 concentration in air would reduce the O_2 concentration to around 17.5% v/v 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 CO_2 on humans can be found in the CO2RISKMAN guidance and in the HSE's "Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment" (HSE).

The dangers of breathing in elevated concentrations of CO_2 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 CO_2 is generally low. Concentrated CO_2 inventories may be present, for example as part of a fire suppression system, but the potential for persons to be exposed to CO_2 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 CO_2 in the order of 10s if not 100s of thousands of tonnes, the potential for widespread exposure to air with hazardous concentrations of CO_2 will exist.

To effectively manage the risks associated with handling large quantities of CO_2, a full understanding of the impact CO_2 has on the human body is required. The CO2RISKMAN guidance provides details of this.

The venting of liquid CO_2 to atmosphere whether through a vent or leak will result in a phase change as the CO_2 depressurises through the release aperture with vapour and solid CO_2 being formed. Anyone caught in the cold jet of gas with potentially entrained solid CO_2 particles will suffer cryogenic burns. Inhalation of such a cold atmosphere would also cause severe internal injuries.

Liquid and particularly supercritical phase CO_2 is a very efficient solvent. When there is substantial reduction in pressure of CO_2 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.

4. HAZARD MANAGEMENT

The number of organisations that could be involved in delivering an integrated CCS operation along with their potential unfamiliarity of the hazards associated with handling very large quantities of CO_2 adds to the challenge of ensuring major accident risks are effectively controlled.

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 CO_2
- 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 CO_2 pipeline)
- Lack of stakeholder awareness and understanding of the potential risks

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. commercial, political, regulatory). 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 CO_2 system or operation. An example would be water and impurity control at the capture facility being a key control measure for leak prevention in the downstream pipelines.

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.).

5. CO_2 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 CO_2 handling system within a CCS project. Details on each can be found in the CO2RISKMAN guidance.

Inadequate Appreciation of CO_2 Hazards: Those responsible for, or have influence over, safety risk management need to have an adequate understanding of the potential hazard that CO_2 and the associated CO_2 stream impurities can pose within the CCS context and scale of operations. Without this there is potential for the CO_2 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 CO_2 is well known but the presence of impurities within the CO_2 stream such as H_2 or N_2 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 short comings 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 CO_2 and particularly supercritical CO_2, is commonly used as an industrial solvent. CO_2 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 CO_2. In addition to its solvent properties, CO_2 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 CO_2. 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: CO_2 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 CO_2 stream may significantly heighten the corrosion rate by forming other acids (e.g. sulphuric, nitric, etc.) and changing water solubility properties. Developing a suitable CO_2 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 CO_2 Formation: Liquid or supercritical phase CO_2 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. CO_2 cannot exist at atmospheric pressure in its liquid phase. The depressurisation of CO_2 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 CO_2. In addition, significant quantities of solid CO_2 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 CO_2 stream, including the effects of the impurities, is of vital importance within the design and operation of CO_2 stream handling systems.

Thermal Expansion: CO_2 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 CO_2 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 CO_2 and particularly supercritical CO_2, 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 CO_2 from a super solvent to a vapour with virtually no solvent capability. Any impurity within the CO_2 stream that is dissolved by the CO_2 and held in solution will therefore be released should the CO_2 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 CO_2 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 CO_2 release that may lead to low temperature embrittlement are due to the Joule-Thomson effect and the formation of solid CO_2 at -78˚C at a leak point, and within the pipeline due to the temperature reduction of the liquid CO_2 caused by the boil-off to sustain a pressure drop (e.g. due to a leak or venting) and from solid CO_2 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 (100–250 m/s, Sergey, 2016) 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 CO_2 pipeline, the depressurisation front may travel at a relatively slow speed.

The approaches and methods to prevent crack propagation in CO_2 stream pipelines are known but the current uncertainty may result in overly conservative designs which could add a significant cost burden to a project.

CO_2 BLEVE: Boiling Liquid Expanding Vapour Explosion (BLEVE) is a very unusual but extremely catastrophic event. The principle behind a CO_2 BLEVE is that a very sudden depressurisation of a pressurised liquid such as CO_2 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 CO_2, mostly involving fire extinguishers. In an accident involving a rupture of a 30 tonne capacity CO_2 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 CO_2 BLEVE. For a CO_2 BLEVE to occur in a vessel it is believed that the CO_2 inventory must be within a defined BLEVE envelope, details of which are given in Level 3 of the CO2RISKMAN guidance. The effect of impurities on the BLEVE potential adds uncertainty to this potential hazard.

Toxic Effects of Pure CO_2: As previously mentioned CO_2 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 CO_2 handling system will be of highly concentrated CO_2 (i.e. >95% CO_2 by volume) and until the release dilutes to a concentration of less than around 5% v/v it will pose a significant hazard to people who may inhale it. CO_2 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 CO_2 cloud of sufficient size and duration to pose a major accident threat would likely require a large and prolonged CO_2 release. Liquid phase CO_2 pipelines will contain tens and sometimes hundreds of thousands of tonnes of CO_2 which, if containment is lost, could foreseeably create a CO_2-rich cloud that could potentially threaten large geographical areas. The size of the visible cloud should not be used as an indication of the CO_2 concentration within the cloud. A large low momentum slumping CO_2 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 CO_2 Mixtures: The presence of impurities in a CO_2 stream may affect the potential inhalation impacts of a CO_2 stream release. Some incidental substances are toxic, such as CO, NO_2, SO_2 and H_2S, and it is important to understand the impact of possible impurities, both in isolation and combined with CO_2 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, H_2S 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 CO_2 releases and current modelling tools and approaches should be adequate to assess the hazard potential from a CCS-scale vapour phase CO_2 inventory. The modelling of liquid and SCF phase CO_2 releases is, however, less developed and this raises the level of uncertainty within hazard assessment. The main challenge associated with modelling these phases of CO_2 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 CO_2 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 CO_2 modelling. There are several gaps and uncertainties with respect to CO_2 modelling that need to be recognised and considered when scoping and undertaking CO_2 release modelling and when making use of the modelling output. These include (with details contained with the CO2RISKMAN guidance) modelling of:

- Pipeline depressurisation
- Vessel depressurisation
- Buried pipeline release
- Subsea pipeline release
- CO_2 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 CO_2 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 CO_2 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 CO_2 during all reasonably foreseeable conditions. Particular consideration must be taken when releasing a CO_2–rich stream in still weather conditions, especially if there is a temperature inversion, since the cold CO_2 stream being released may slump towards the ground or water surface with relatively low dispersion rates.

6. CO_2 STREAM GENERIC HAZARDS

The CO2RISKMAN guidance provides information that can be used to assist in the hazard identification of CCS CO_2 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 CO_2 stream aspects and therefore does not seek to address non-CO_2 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 CO2RISKMAN guidance to stimulate thinking and discussion within normal CCS project hazard identification and assessment processes.

Included within the CO2RISKMAN guidance are details on the following:

Potential loss of containment (leak) causes:

- Inappropriate human input or action during the design, operation, maintenance, intervention, etc., due to a lack of relevant CO_2 competency and/or experience
- Low temperature embrittlement of containment envelope due to rapid depressurisation of a liquid phase CO_2 inventory
- Low temperature embrittlement of containment envelope due to CO_2 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 CO_2
- 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
- CO_2 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 supply vessels in close attendance to an offshore platform

Potential Consequences:

- Inhalation of elevated CO_2 concentrations in air
- Inhalation of hazardous levels of CO_2 stream impurities
- Inhalation of, or exposure to, very cold air mixture
- Contact with solid CO_2 or cooled surfaces
- Rapid expansion
- Projectiles
- Lack of visibility
- Loss of structural integrity due to low temperature embrittlement

7. CONCLUSIONS

There is an exponential growth in CCS across the globe to support the drive for rapid, widescale decarbonisation. The consequence of this is that many CCS CO_2 system developers, operators and regulators, people who have influence on controlling the associated major accident risks, may have a lack of understanding of the properties and characteristics of CCS CO_2 and how these can lead to, or result in, major accidents.

Commercial CCS projects will handle very large quantities of CO_2 with inventories of tens if not hundreds of thousands of tonnes. A significant CO_2 leak from one of these large inventories could result in widespread loss of life because of the formation of a physically large, slow moving, cold, slumping gas cloud with CO_2 concentration above that which results in toxicological impact (>5% v/v). And, on a more strategic level, such a leak would likely cause negative public perception and acceptance concerns for CCS implementation. Of particular concern are buffer storage and pipelines containing liquid phase CO_2 located onshore, in shipping ports, or near-shore as these will have the combination of large CO_2 inventory, phase change issues should a leak occur, and likely proximity to the public or industrial sites.

It is vital that those responsible for promoting, implementing and regulating CCS are fully aware of the major accident potential associated with large inventory CO_2 containment systems so that they can be located, designed, operated and maintained to reduce the risks to people (and industry) to an acceptably low level.

The CO2RISKMAN guidance is a comprehensive and robust industry knowledge source for the CCS industry to help CCS projects and operations understand the issues, challenges and hazards associated with handling very significant CO_2 flows and inventories so that they can develop and implement robust strategies to deliver effective major accident hazard management.

There is no reason why handling very large quantities of CO_2 within CCS systems 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 along with other CCS industry guidance and recommended practices is available from www.dnv.com/ccus.

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