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Carbon dioxide capture, transportation and geological storage — Cross cutting issues — Flow assurance

Captage, transport et stockage géologique du dioxyde de carbone — Questions transversales — Maintien de l'écoulement

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Foreword

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This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

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Introduction

Flow assurance can be defined as an engineering discipline that is required to understand the behaviour of fluids inside vessels, pipes or porous media at flowing and at static conditions. Flow assurance provides input to design activities, such as pipeline design or risk analysis. It emerged as an engineering discipline in the oil and gas industry in the 1990s. Flow assurance analysis is delivered in the oil and gas industry by methodical numerical simulation of each pipeline and injection/production well operating case, often using flow assurance software to facilitate the analysis.

In relation to carbon dioxide capture and storage (CCS), flow assurance seeks to maintain the continuous supply of the CO_2 stream from the capture plant, through the transportation system and into the geological reservoir via injection wells. Flow assurance is required to demonstrate that all foreseeable operating modes of all components of CCS projects, planned and unplanned, are predictable, reliable and safe. It achieves this through analysis of the CO_2 stream flowing as a fluid in the various components of a CCS project's systems, from capture through to geological storage (capture, transport, injection and storage).

Some of the key issues of interest addressed by flow assurance analysis include:

— the total network or project hydraulic capacity requirements necessary for determining pipeline, injection well and reservoir operating parameters;

— management of transient operations, such as those caused by varying injection rates, varying CO_2 stream supply and during slugging, surging and start-up and shut-down operations;

— thermal management under various operational scenarios to ensure that the variations of fluid temperature are within the operating constraints of the system;

— fluid phase behaviour and physical properties as a function of CO_2 stream composition;

— hydrate management and control, resulting from Joule-Thomson effects such as pressure drop across pressure reducing valves, orifice plates and flow metering devices; and

— planned and unplanned de-pressurization of systems, such as that resulting from a pipeline rupture, well blowout or controlled venting of pipeline and equipment during maintenance activities.

Most of the above issues can be addressed by dedicated flow assurance modelling software and tools, in which both thermodynamic and hydrodynamic behaviours of fluids in technical components such as pipelines or wells are modelled. The thermodynamic properties and transport properties of fluids are closely related to their chemical composition and their associated amount or concentration. Significant differences in thermodynamic behaviour of fluid of different compositions can be observed and these differences can lead to different hydrodynamic behaviour of the flow. Therefore, fluid thermodynamic properties are a critical input to the dynamic flow models.

Existing CCS system modelling of technical components has mainly been limited to single phase CO_2. Given significant storage capacity suitable for permanent CO_2 storage exists in depleted hydrocarbon reservoirs, which can be initially at pressures where CO_2 can be subject to two-phase flow conditions, the CO_2 stream in the pipeline and injection well can be subject to two-phase flow conditions, i.e. a combination of two CO_2 phases, gas and liquid. Two-phase flow can also occur during transient operations such as opening up, closing in or depressurization of pipelines or wells. Within underground reservoirs two-phase flow is generally expected involving the injected CO_2 stream as well as formation fluids that will have to be mobilized. Facilitating unhindered flow of the CO_2 streams in CCS projects requires the inclusion of reservoir fluids (natural gas, water or crude oil) and relevant processes in the storage reservoir in the flow assurance analysis. Two-phase flow cases, such as in the examples mentioned, are a more complex challenge for flow assurance modelling compared to flow assurance in oil and gas transportation and injection/production well infrastructure.

Existing commercial software tools for flow assurance analysis are utilized for modelling the planned and unplanned operation modes for the various components of the CCS system, including the reservoir management component. These tools predict fluid behaviour and properties in the operating system. As input, this modelling requires input data such as the CO_2 stream composition, the physical geometry of relevant infrastructure such as pipelines, injection wells and the receiving reservoir, and the operating conditions which include:

— steady-state and transient processes;

— single-phase and multiphase flow;

— pressure, temperature, phase fraction, velocity, etc., and their distribution in space and time; and

— distribution of fluid phase compositions in both time and space.

Carbon dioxide capture, transportation and geological storage — Cross cutting issues — Flow assurance

1 Scope

This document describes and explains the physical and chemical phenomena, and the technical issues associated with flow assurance in the various components of a carbon dioxide capture and storage (CCS) system and provides information on how to achieve and manage flow assurance. The gaps in technical knowledge, limitations of the tools available and preventative and corrective measures that can be taken are also described.

This document addresses flow assurance of CO_2 streams in a CCS project, from CO_2 capture via transport by pipeline and injection well through to geological storage. It does not specifically address upstream issues associated with CO_2 sources and capture, although flow assurance will inform CO_2 capture design and operation, for example, on constraints on the presence of impurities in CO_2 streams, as there are too many different capture technologies to be treated in detail in this document.

Vessel transport and buffer storage that are considered in integrated CCS projects under development, are not covered in this document. Flow of material in the supply chain of a CO_2 source, even if delivered by a pipeline (e.g. blue hydrogen generation), and flow of gas streams within facilities generating and feeding these into a capture facility can impact flow assurance in CCS projects and networks. These are out of the scope of this document as well.

This document also examines the impact of impurities on the phase behaviour and physical properties of the CO_2 stream which in turn can ultimately affect the continuous supply of the CO_2 stream from the capture plant, through the transportation system and into the geological reservoir via injection wells.

Flow of fluids in oil reservoirs for the purpose of enhanced oil recovery is not within the scope of this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 27917, *Carbon dioxide capture, transportation and geological storage — Vocabulary — Cross cutting terms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 27917 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
carbon dioxide capture and storage network
CCS network
connections of multiple CO_2 sources and storage sites

3.2
carbon dioxide capture and storage project
CCS project
either single capture-transportation-storage systems or multiple systems (networks) consisting of CO_2 capture systems, CO_2 transportation systems, and CO_2 geological storage systems

Note 1 to entry: In this document, the facilities generating a CO_2 stream are included in the considerations of flow assurance, as part of any decision or event at these facilities affecting the amount of CO_2 stream sent to the capture system, and will impact flow assurance within the CCS project.

Note 2 to entry: For more information on

— CO_2 capture systems, see ISO/TR 27912,

— CO_2 transportation systems, see ISO 27913, and

— CO_2 geological storage systems, see ISO 27914.

3.3
carbon dioxide capture and storage system
CCS system
combination of the capture, transportation and storage components considered as a single entity

3.4
component
assemblage of technical or geotechnical installations and natural features of subsurface geological systems that are separate in terms of physical space, technical disciplines, industrial practice and dominating physico-chemical processes

3.5
flow regime
type of flow pattern developed by fluid flowing through pipes

Note 1 to entry: Flow regimes depend on pressure and temperature dependent fluid properties, the diameter of the pipe, flow rates, fractions of each phase and the inclination of the pipe. Flow regimes can change with distance along a pipeline. In single phase flow, the regimes laminar and turbulent flow are distinguished.

3.6
hydraulic capacity
maximum flow rate achievable in a system for a given pressure loss

4 Abbreviated terms

BHP	bottom hole pressure
BHT	bottom hole temperature
CCS	carbon dioxide capture and storage
DHSV	down-hole safety valve
EoS	equation of state
EOR	enhanced oil recovery
HET	hydrate equilibrium temperature
MEG	mono-ethylene glycol
RFO	ready for operation

SSSV subsurface safety valve

THMC thermal, hydraulic, mechanical and chemical

WAG water alternating gas

5 Overview of the necessity of flow assurance in CCS projects

5.1 General

During normal operations, CCS projects are generally designed to deliver an uninterrupted supply of a CO_2 stream:

a) to and from the capture plant;

b) through the transportation system, such as pipelines;

c) into the geological storage reservoir including the injection wells and surface infrastructure; and

d) within the storage reservoir.

Most CCS projects will be associated with fluctuating operating characteristics and conditions, i.e. varying inflow and outflow behaviours. Detailed consideration of these characteristics during the design and planning of the individual components of CCS projects need to be coupled in a way that can minimize the risk of flow interruptions of the CO_2 streams through the entire CCS project to as low as practicable. To best achieve this, the overall system fluctuations of pressure, temperature, fluid velocities and flow rates of CO_2 streams and their gradients are kept within the predefined operational ranges for these parameters at each CCS component as determined from the flow assurance modelling during the design phase of the project. The design of technical components can include means to facilitate preventive and corrective measures to achieve these operational ranges.

Notwithstanding that it would be ideal to maintain uninterrupted flow, in reality, like all industrial processes, interruptions caused by planned or unplanned events are inevitable, for example, maintenance work or unexpected equipment failure or in EOR operations injecting water and CO_2 (WAG schemes) intermittency is inherent to normal operations. Therefore, flow assurance requirements need to make provision for such fluctuations and events.

5.2 Reasons to maintain flow assurance

There are several reasons for ensuring uninterrupted flow along the entire CCS chain including:

— Technical and safety**:** Flow interruptions or excessive fluctuations of CO_2 stream properties (including mass flow rate, pressure and composition) increase wear of equipment and the risk of early failure due to physical or chemical effects. Chemical effects can include the formation of hydrates that can block pipes or reservoir rocks and corrode the equipment. Physical effects include vibrations, temperature effects on material integrity or mobilization of fine particles and blocking of pore throats in porous reservoir rocks. Rather sudden fluctuations of physical properties in CO_2 streams can result from phase changes or fluid dynamic effects (e.g. hydraulic hammer) that can damage infrastructure.

— Economic: Maintenance and replacement of equipment is a cost factor. A smaller than forseen amount of CO_2 stored will reduce the income of CCS projects, e.g. from emission trading or tax credit generation as well as for transport and storage service providers. Excess CO_2 that cannot be captured, transported or stored and thus will be released to the atmosphere can result in payments for emissions. Furthermore, releasing captured CO_2 downstream is associated with unnecessary costs for the capture operation.

— Environmental: Venting of CO_2 will be counter to the purpose of climate mitigation by CCS projects and can release substances into the environment that are harmful to the human health or the environment. The nature and concentrations of such substances depend on the capture technology. Lower than anticipated amounts of CO_2 captured, transported and stored will reduce the overall energy, resources and environmental balances of CCS projects.

5.3 Potential factors affecting flow of CO_2 streams at individual components of CCS projects

5.3.1 General

As illustrated in Figure 1, the essential components of a CCS project that can impact flow of CO_2 streams are CO_2 sources, capture facilities (including purification and conditioning units), transportation infrastructure, manifolds for field distribution, injection wells and storage reservoirs.

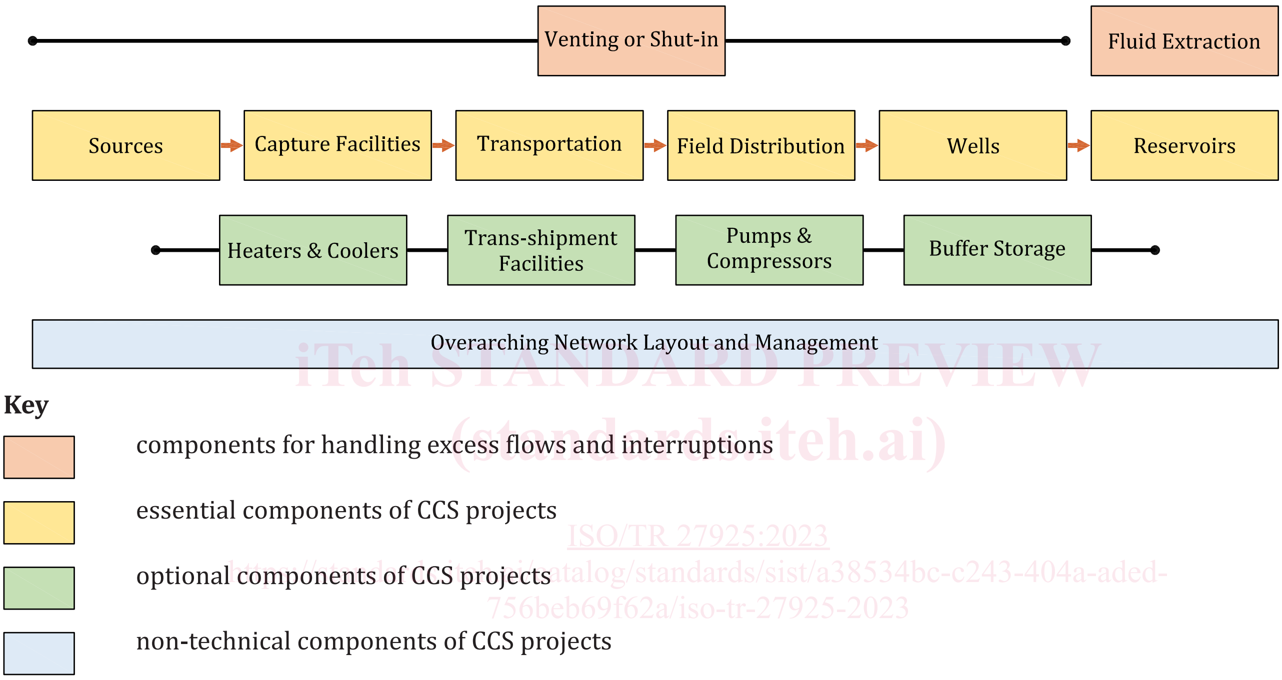

Figure 1 — Schematic overview of the components of CCS projects — CCS systems or networks

Essential components for a single source-to-sink scenario are connected by brown arrows in Figure 1. Optional components and devices, that are not needed in every project, can be included at various locations within CCS projects, including trans-shipment facilities, pumps, compressors, heaters, coolers and buffer storage. Further technical components for managing flow interruptions or excess streams, likely to be installed in any CCS project, include venting or shut-in devices, e.g. safety valves along a pipeline.

Besides the technical components that impact flow assurance, management procedures will determine the overarching flow assurance within CCS projects. Flow assurance becomes a more complex issue for the overarching layout and management, for example when transportation networks connect multiple sources and sinks and facilitate alternative routing and means for transportation.

The continuous flow of CO_2 streams in CCS projects can be disturbed by flow rates above or below limits of normal operations. Counter measures can be the venting of a part of the gas streams (exhaust gas, process gas or CO_2 stream) or shut-in of equipment. Provisions for venting or shut-in can be located at multiple sites within CCS projects or within the essential components. Extraction of fluids, CO_2 stream or other formation fluids, from a storage reservoir can also be used to maintain continuous flow. For example, in the case of storage in saline aquifers, production of brine and its reinjection into other formations can be utilized for the purpose of pressure management.

Other than malperformance and failure of components, threats to flow assurance within each of the various CCS components are described in 5.3.2 to 5.3.8.

5.3.2 CO_2 sources

The CO_2 generation at the sources can vary or change for different reasons and at different timescales. The production of goods can be subject to market fluctuations that will be associated with equivalent fluctuations of industrial plants' CO_2 output. Some fluctuations can be foreseeable, such as seasonal fluctuations or planned maintenance and shut-downs. Other changes can occur on a timeline that is difficult to predict, for example, the generation of process heat can switch from coal to natural gas or hydrogen which can result in future that can lead to a permanent decrease in the generation of CO_2. This decrease and associated changes of the CO_2 concentrations in the process or flue gas stream can require changes to the capture technologies deployed. In networks of multiple sources, changes at individual sources can be levelled-out and the effects on the flow of the combined CO_2 streams can be compatible with the foreseen operational window for downstream infrastructure (see ISO/TR 27918). It is therefore necessary for the design of the various CCS components to accommodate a wide operating envelope including situations of turndown.

5.3.3 Capture facilities

The capture technologies including gas conditioning processes, determine the concentrations of impurities in CO_2 streams. The efficiency of capture processes depends on the mass flow and composition of gas streams – and their variations in time. Capture facilities and their equipment are designed to work in an optimal way within the design window of operation. Excess fluctuations of gas streams both in terms of composition and mass flow rates can lead to sub-optimal operation outside of the design window and to a reduced capture efficiency. Combining CO_2 streams from different sources and thus containing a different set of impurities can cause reactions between impurities that can result in products that can increase risks for flow assurance in downstream infrastructure, e.g. by increasing corrosion, friction, wear or deposition of products in pipelines. Thus, effort in the removal of impurities from the CO_2 stream can be required before transportation, or else combining of CO_2 streams can be prevented, if the mixture is incompatible with downstream components; see Reference [2].

5.3.4 Transportation

While the transportation of CO_2 in pipelines aims at achieving uninterrupted flow of CO_2 in a single dense phase (see ISO 27917) at ambient temperatures and high pressure, transport in vessels (road, rail, ship) are expected to be in a liquid phase at very low temperatures and moderate pressure. If physical properties of CO_2 streams in upstream and downstream infrastructure are different from that in the transportation system, installations have to be provided at either end of the transportation chain to adjust physical conditions. This equipment includes compressors, pumps, heaters and coolers. The impact of these on flow assurance depends on the technology utilized, the location of such equipment within the CCS project, and the designed range of flow rates (and CO_2 stream compositions) that these can handle.

Furthermore, the transport in vessels is inherently discontinuous, i.e. leads to intermittent transportation that requires some sort of buffering. Buffering can be achieved by pressure changes in pipelines (line packing), use of temporary stores (engineered or geological) or switching between a suitable number of vessels to ensure continuous filling and discharge of vessels, so that up- and downstream CO_2 can flow in a continuous manner. Overall, vessel transportation is more sensitive to external impacts than pipeline transportation, e.g. due to road or rail blockings, extreme water levels in rivers or off-shore storms that can interrupt shipping. Thus, additional dedicated buffers can be prudent in order to avoid interruptions, shut-ins and venting of CO_2.

5.3.5 Field distribution

In large scale storage projects, usage of several wells can facilitate CO_2 injection into reservoirs. Natural gas and oil reservoirs are usually exploited by a considerable number of wells, which can be used in active or depleted fields for CO_2 injection. A CO_2 stream arriving from distant sources has to be distributed within the hydrocarbon fields through manifolds to the individual wells in order to fill the reservoir in an effective manner. In particular, the CO_2 demand of wells in EOR projects will be variable according to the oil production operation. For example, in WAG schemes, CO_2 is injected intermittently in individual wells. Trade-offs between optimum oil recovery and maximum CO_2 storage can be made in CO_2 EOR projects, that will be influenced by the revenues or savings from CO_2 storage and oil sale. Additional fluxes of CO_2 streams are associated with technical components for the separation of CO_2 from crude oil and formation water and recycling it to the injection wells.

Also, in aquifer storage, manifolds can be used for distributing CO_2 streams between injection wells in one or more reservoirs. Wells can be laterally spaced in one storage formation, as in the case of the Krechba storage site (Algeria), or tap reservoirs at different depths, such as in the Snøhvit field (Norwegian Continental Shelf). Benefits of using more than one well for injection into saline aquifers include the possibility to react in the case of injectivity or containment problems, the ability for switching between wells in the case of maintenance or logging in a well, or the options for pressure management and plume steering in the storage reservoir. This flexibility suits the flow assurance in the upstream components of CCS projects.

5.3.6 Injection wells

Similar to pipelines, injection wells need to maintain flow of CO_2 streams at rather constant conditions. However, the physical conditions of CO_2 streams can differ considerably from top to bottom of a well, especially if reservoir pressures are much lower, e.g. in depleted natural gas reservoirs than at the end of transportation pipelines or temperatures are much higher in the reservoirs compared to the low temperatures of liquid CO_2 in ships. Such contrasting conditions hold technical challenges for design and operation of injection infrastructure. Technical challenges include avoiding the formations of hydrates that can block flows and phase changes or thermal and/or hydraulic stresses that can impair well integrity. Corrosion or mechanical wear can lead into situations that can require monitoring (using logging), maintenance or work-overs on one or more injection wells. Wells can be out of service because of such operations for a while. Therefore, avoiding of early well workover is one of the aims for flow insurance in injection wells.

In particular, offshore CO_2-injection wells sometimes have to be operated under transient or intermittent conditions. In case of pipeline transportation, this can be due to varying CO_2 supply, and in the case of ship transportation, it can be due to the arrival of ships and the lack of buffer storages. From a study into the effect of thermal cycling in the well due to intermittent injection from ships (see Reference [3]), it was found that long intervals, low CO_2 temperatures and high injection rates lead to the highest thermal stresses in the well. Depending on the well materials and construction, those stress levels can impact well integrity showing the importance of considering thermal and mechanical stresses in the well design for cyclic injection operation.

5.3.7 Storage reservoirs

Natural rocks are heterogeneous at different scales. Sedimentary structures in the centimetre to decimetre range and beyond affect bulk hydraulic properties, such as permeability. Tectonic structures and variations of the sedimentary depositional environment in the scale of tens to thousands of metres can result in the compartmentalization of reservoirs, impacting plume migration, brine displacement, pressure build-up and injectivity of wells. The resolution of seismic images is low compared to the size of sedimentary or tectonic structures affecting fluid flow and rock samples obtained from well drilling are usually too small to be representative for a larger reservoir volume. Thus, parameters required for “precise” prediction of fluid flow in reservoirs are not available in the required resolution and full spatial coverage. Numerical models describe fluid flow in reservoirs in simplified ways, assuming generalized parameter distributions at rather coarse scales. Hence, CO_2 plumes will not spread out in natural reservoirs “exactly” as predicted by numerical models. An example of such structures that had not been resolved in seismic images before the injection of CO_2 are the shale layers within the Utsira sand at the Sleipner CCS project, that have a marked impact on the shape of the CO_2 plume within the reservoir, see Reference [4]. Thus, the uncertainties regarding actual injection rates, pressure build-up, spreading of CO_2 plumes and the displacement of formation fluids can be large and can impact the overall CO_2 uptake of a reservoir. An example of the impact of storage properties is the experience in the

Tubåen Formation storage reservoir within the Snøvit CCS project offshore Norway, see References [5] and [6]. At the given injection rates, pressure within the reservoir built up faster than anticipated requiring additional injection wells to be drilled beyond the area influenced by this premature pressure build up. During project lifetime, reservoir models generally will be updated based on operational and monitoring data to increase conformance between models and real plume behaviour and reduce uncertainties in predictions.

5.3.8 Optional components

In addition to the essential components, CO_2 streams can pass optional installations along the route of CO_2 transportation, such as trans-shipment facilities, pumps, compressors, heaters, coolers, buffer storage, venting or shut-in devices, e.g. safety valves along the CCS chain as described in Figure 1. The impact of these on flow assurance depends on the used technology, the positions within a CCS chain or network, and the specified range of flow rates and CO_2 stream compositions that these can handle.

5.4 Providing flow assurance

5.4.1 General

Assuring a stable flow of CO_2 streams through a CCS chain or network can be secured by preventative and mitigative or corrective measures. Reducing the risks of intermittent flow will likely require a project-specific balanced mix of the two approaches. Consequences of interruptions, costs, damage of reputation etc., can be criteria for the selection of measures for flow assurance.

5.4.2 Technical design

A key parameter for the appropriate design capacity for CCS projects is the expected total mass flow of a CO_2 stream and its variation over the project lifetime. High flexibility of equipment for variable flow rates is beneficial for flow assurance. In single source-sink chains, the component with the least flexibility will dictate the flexibility of the entire project to cope with fluctuations or interruptions. Redundancy of limiting components or the use of modular components can increase the flexibility of the entire project. Several units of capture facilities, pumps or injection wells can be combined for the enhancement of the overall flexibility.

Generally, storage reservoirs cannot be modified, apart from fluid extraction for pressure management or in the event injection creates, propagates or activates faults in the formation or confining layers. Thus, storage site exploration can include the surroundings (laterally and vertically) of storage formations so that additional storage volume can be tapped into if required.

Large volume buffer storage or reserve storage, e.g. in depleted fields with re-usable infrastructure, can be used for captured CO_2 that cannot be transported and stored according to the planned regular operation.

5.4.3 Operational procedures and work-flows

Where flow interruptions are unavoidable, a process for prioritising sites in CCS projects where CO_2 can be released or shut-in with the least detrimental impact can be employed. These can vary depending on the site in a CCS project where the flow is interrupted first. It is important to undertake the sequence of shut-ins and venting as well as velocities of ramp down (and up) in a manner that will minimize impacts on equipment of the entire chain. To mitigate this, as part of the preparation for such shut-down events, it is important to communicate the measurement and control technology between different components of a CCS project and the appropriate and safe response to such pre-determined and expected events. This can be challenging if different owners and operators are involved, and if addressed possibly through overarching project management.

For planned flow interruptions in CCS projects, such as those experienced during maintenance shutdowns, continuous flow, can be maintained via either use of buffer storage or availability of back up equipment to minimise variations of flow and phase behaviour of the CO_2 stream, or both.