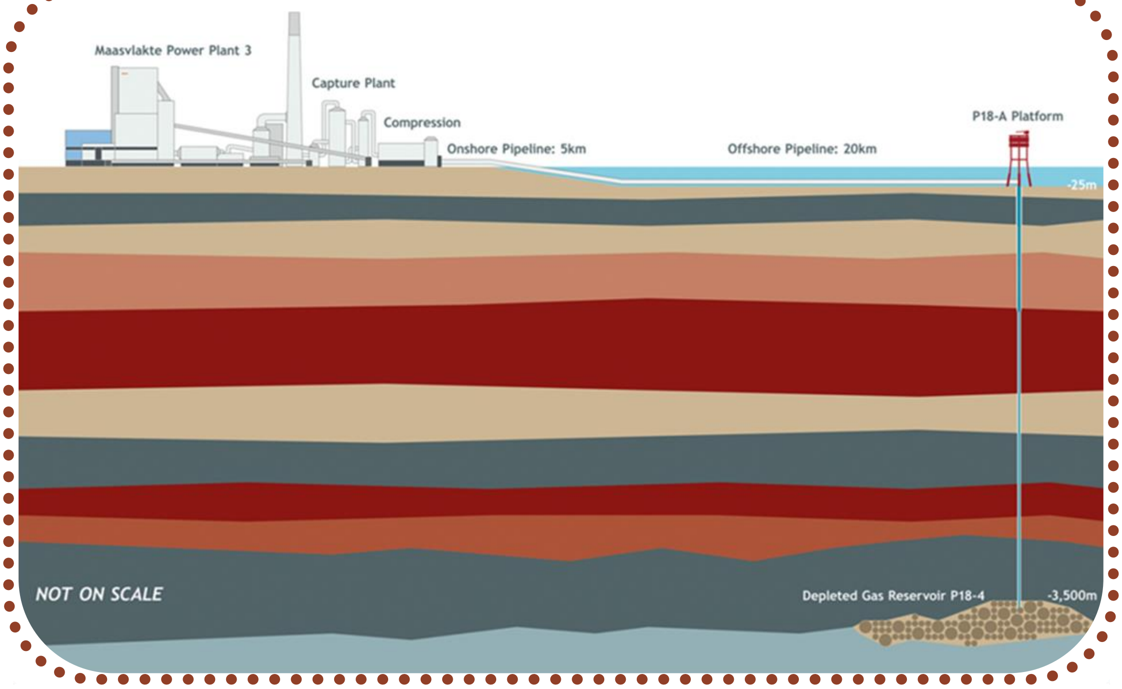
Flow Assurance & Control Philosophy

Rotterdam Opslag en Afvang Demonstratieproject

Special Report for the Global Carbon Capture and Storage Institute



Maasvlakte CCS Project C.V.

Date : July 2013

Version : Final

SUPPORTED BY

GLOBAL CCS INSTITUTE

Government of the Netherlands

Co-financed by the European Union
European Energy Programme for Recovery

Title
Flow Assurance & Control Philosophy ROAD
Special Report for the Global Carbon Capture and Storage Institute

Authors
Jan Uilenreef
Marc Kombrink

Date
31 July 2013

ROAD | Maasvlakte CCS Project C.V.

Parallelweg 1	P.O. Box 133
3112 NA Schiedam	3100 AC Schiedam
The Netherlands	The Netherlands

Tel: +31 10 75 34 000
Fax: +31 10 75 34 040
E-mail: info@road2020.nl
Web: www.road2020.nl

Disclaimer
The ROAD project is co-financed by the Government of the Netherlands, the Global Carbon Capture and Storage Institute and the European Commission under the European Energy Programme for Recovery. The sole responsibility for the content of this publication lies with Maasvlakte CCS Project C.V.

This report for the ROAD project is being provided pursuant to the funding agreement between the Global Carbon Capture and Storage Institute and Maasvlakte CCS Project C.V. The provisions of that funding agreement are for the sole protection and legal benefits of the parties thereto, unless otherwise agreed in writing. No other person or entity shall have any direct cause of action or claim against any of the parties to that funding agreement arising from the publication, disclosure or distribution of this report and/or the utilization of or reliance on the content of this report.

This document is published on the Global CCS Institute's website in the interest of information exchange. The Global CCS Institute does not give any representation or warranty as to the reliability, accuracy or completeness of the information, nor does it accept any responsibility arising in any way (including by negligence) for errors in, or omissions from, the information.

Table of Contents

Table of Figures

List of Abbreviations

bara	bar absolute
barg	bar gauge
cm	centimetre
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
EEPR	European Energy Programme for Recovery
FAS	Flow Assurance Study
Global CCS Institute	Global Carbon Capture and Storage Institute
km	kilometre
MCP	Maasvlakte CCS Project C.V.
mm	millimetre
MPP3	Maasvlakte Power Plant 3
Mt	megatonne
MWe	megawatt electrical
RCI	Rotterdam Climate Initiative
ROAD	Rotterdam Opslag en Afvang Demonstratieproject

Management Summary

ROAD is the Rotterdam Opslag and Afvang Demonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the first large-scale, integrated Carbon Capture and Storage (CCS) demonstration projects on power generation in the world. The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain on power generation.

One of the key challenges for a demonstration project like ROAD is to safely and efficiently operate the CO_2 stream of an integrated Carbon Capture and Storage chain: capturing the CO_2 from the flue gases of a coal-fired power plant, compressing and transporting the CO_2 through a 25 km pipeline to an offshore platform and injecting the CO_2 into a depleted gas reservoir 3.5 km below the sea bed.

This special report 'Flow Assurance and Control Philosophy' of the ROAD project is drafted for the Global Carbon Capture and Storage Institute (Global CCS Institute). It provides an insight into the proposed control and operating philosophy of the CO_2 stream of the integrated CCS chain of ROAD (at high level) in steady state, shutdown and start-up conditions.

Although it has not been practiced before, the Flow Assurance Study (FAS) conducted by ROAD has clearly shown that filling a reservoir of (very) low pressure to an end pressure of 300 bar is in practice possible, but one has to study the behaviour of CO_2 in all its thermo-dynamic aspects with the parameters of the physical configuration of the transport system.

The FAS has resulted in sound and safe procedures for the following operating cases:

- Initial and normal start-up
- Planned start-up after a planned shutdown
- Planned shutdown
- Planned start-up after a non-planned (emergency) shutdown
  - By Capture Plant operation
  - By Platform operation

In this special report it has been pointed out that the CO_2 should be transported warm at low reservoir pressures and start-up to minimize low temperatures and slugs. Slugs may still occur at start-up, but will not do any harm, as long as the simulations are aimed to determine the maximum forces in the pipeline and the platform piping, and the design and construction of the equipment on the platform are resistant to these forces.

1. Introduction

ROAD is the Rotterdam Opslag and Afvang Demonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the first large-scale, integrated Carbon Capture and Storage (CCS) demonstration projects on power generation in the world. The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain on power generation.

One of the key challenges for a demonstration project like ROAD is to safely and efficiently operate the CO_2 stream of an integrated Carbon Capture and Storage chain: capturing the CO_2 from the flue gases of a coal-fired power plant, compressing and transporting the CO_2 through a 25 km pipeline to an offshore platform and injecting the CO_2 into a depleted gas reservoir 3.5 km below the sea bed.

Previous to this special report, the ROAD project published special reports for the Global CCS Institute on:

- Lessons learnt.
- Handling and allocation of business risks.
- Project execution strategy.
- Stakeholder management.
- Permitting process.
- Mitigating project risks.
- Non-confidential FEED study.
- CO_2 technology selection methodology.

This special report 'Flow Assurance and Control Philosophy' provides an insight into the following topics:

- The proposed control and operating philosophy (at high level) in steady state, shutdown and start-up conditions.
- Single phase and two-phase flows in the system (from compressor discharge to well bottom).
- Use of a control valve and heater on the platform (advantages and disadvantages).
- Pressure and temperature changes in the system as the reservoir fills.

The report starts with an introduction of the project, basic specifications and the integrated CCS chain of the ROAD project. Subsequently, the specific design parameters and data of ROAD and the conducted Flow Assurance Study (FAS) are described. Based on this framework, a Control and Operating Philosophy is developed and explained. Finally, the main conclusions and recommendations of the report are presented.

2. Project Factsheet

2.1 Project Overview

ROAD is the **R**otterdam **O**pslag and **A**fvang **D**emonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the first large-scale, integrated Carbon Capture and Storage (CCS) demonstration projects on power generation in the world.

2.1.1 Project objectives

The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain on power generation. In the power industry, to date, CCS has primarily been applied in small-scale test facilities. Large-scale demonstration projects are needed to show that CCS is an efficient and effective CO_2 abatement technology within the next 5 to 10 years. With the knowledge, experience and innovations developed by projects like ROAD, CCS could be deployed on a larger and broader scale: not only on power plants, but also within energy intensive industries. CCS is one of the transition technologies expected to make a substantial contribution to achieving climate objectives.

2.1.2 Partners

ROAD is a joint project initiated by E.ON Benelux N.V. and GDF SUEZ Energie Nederland N.V. Together they constitute the limited partnership Maasvlakte CCS Project C.V. The intended partners of ROAD are GDF SUEZ E&P Nederland B.V. for the CO_2 transport and TAQA Energy B.V. for the CO_2 injection and permanent storage. The ROAD project is co-financed by the European Commission within the framework of the European Energy Programme for Recovery (EEPR) and the Government of the Netherlands. ROAD is knowledge partner of the Global Carbon Capture and Storage Institute (Global CCS Institute) and has received financial support in this regard.

2.1.3 Project specifications

ROAD applies post combustion technology to capture the CO_2 from the flue gases of a new 1,070 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the Rotterdam port and industrial area. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 Mt of CO_2 per year. The capture installation is planned to be operational in 2017.

Figure 1: Location of ROAD project: Port of Rotterdam and North Sea

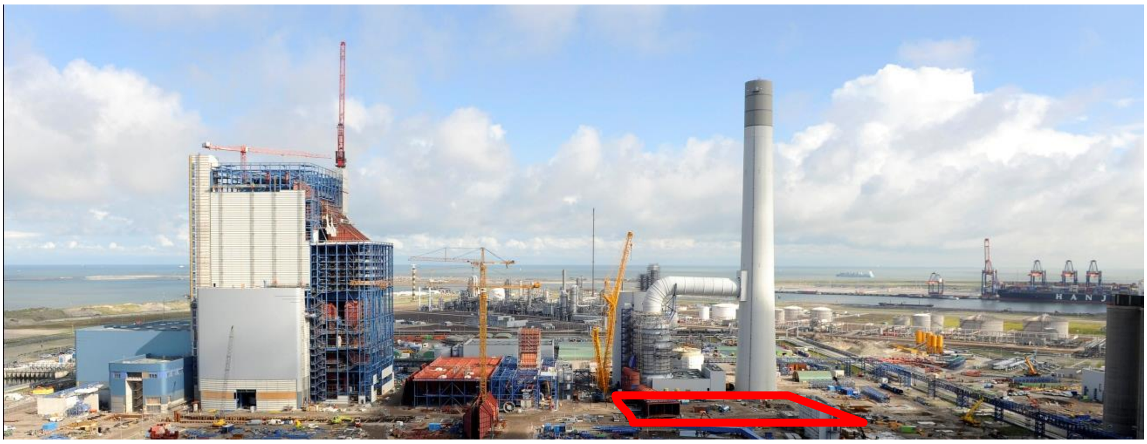


Figure 2: Proposed location of capture unit: Maasvlakte Power Plant 3 (photo: E.ON)

From the capture unit the CO_2 will be compressed and transported through a pipeline: 5 km over land and 20 km across the seabed to the P18-A platform in the North Sea. The pipeline has a planned transport capacity of 1.5 Mt of gaseous CO_2 per year (equivalent to 5 Mt CO_2 per year in dense phase). It is designed for a pressure of 140 barg and a temperature of 80 °C.

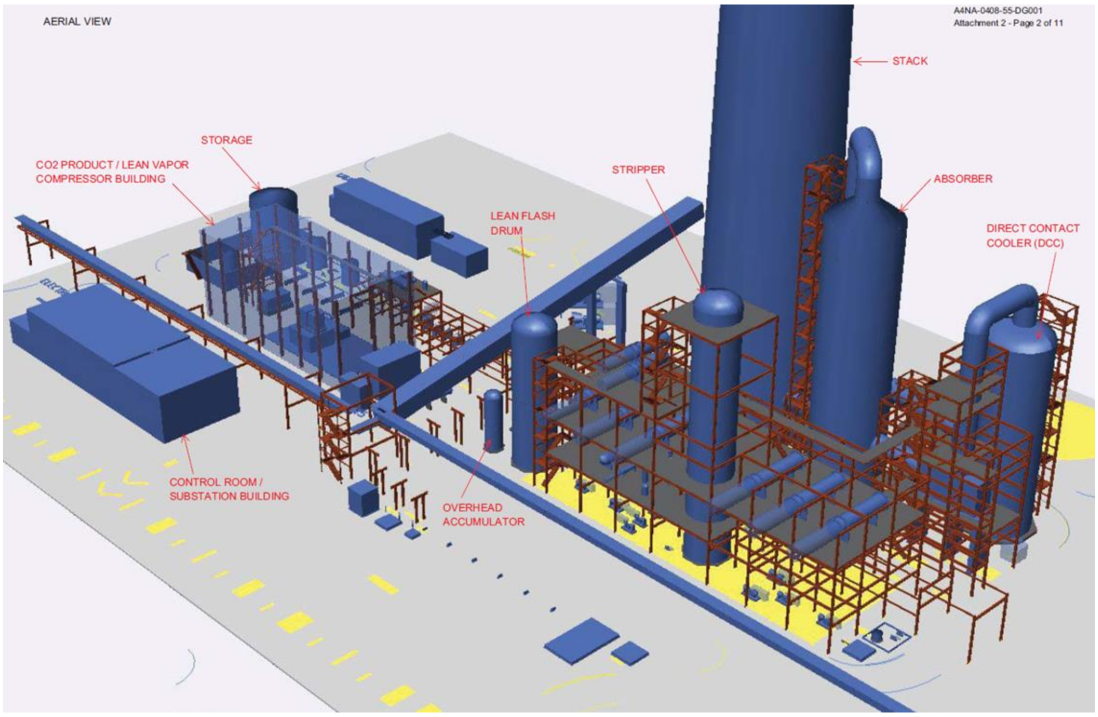


Figure 3: Technical design (Fluor) of 250 MWe equivalent post combustion capture plant

ROAD plans to store the captured CO_2 in a depleted gas reservoir under the North Sea. These gas reservoirs are located in block sector P18 (P18-6, P18-4 and P18-2) of the Dutch continental shelf, 20 km off the coast. The depleted gas reservoirs are at a depth of 3.5 km under the seabed of the North Sea. The CO_2 will be injected from the platform into depleted gas reservoirs. The estimated storage capacity of P18 is 35 Mt in total.

2.1.4 Rationale for Rotterdam port and industrial area

The Rotterdam port and industrial area has a number of advantages creating favourable conditions to implement a CCS demonstration project like ROAD. The Rotterdam port and industrial area has many CO_2 point sources. Several new coal-fired power stations are under construction and are being built as capture ready facilities. It is relatively close to a large number of (almost) depleted gas reservoirs on the continental shelf under the North Sea, allowing for a small transport distance. These gas reservoirs meet the physical and geological properties for CO_2 storage and will become available from 2014 onwards. Furthermore, the Netherlands has a lot of knowledge and experience with both oil and gas extraction and storage of gas in aquifers and gas reservoirs. Finally, the complete CCS chain (e.g. storage) is remote from inhabited areas. Stakeholders in the direct vicinity of the capture site and the onshore pipeline are other industries. Municipalities neighbouring this part of the port and industrial area are e.g. Westvoorne and Hoek van Holland.

Figure 4: P18-A platform at the North Sea (photo: TAQA)

2.1.5 Facts & figures

Base installation: E.ON Maasvlakte Power Plant 3 (Rotterdam, The Netherlands)

- Output : 1,070 MWe
- Efficiency : 46%
- Operational : 2013
- Capture ready

Capture Plant

- Technology : post combustion
- Capacity : 250 MWe equivalent
- Capture rate : 90%
- CO_2 captured : ~ 1.1 Mt/a
- Operational : 2017

Transport

- Insulated pipeline
- Diameter : 16 inch
- Distance : 5 km onshore, 20 km offshore
- Capacity : 1.5 Mt/a in gaseous phase
  5 Mt/a in dense phase
- Design specifications : pressure 140 barg
  temperature 80 °C

Storage

- Depleted gas reservoir : P18-4
- Operator : TAQA
- Depth : 3.5 km
- Estimated capacity : 8 Mt (for P18-4 only)
- Available : 2014

2.1.6 Planning

The high level schedule of the ROAD project is as follows:

14 July 2009	:	Application submitted for funding under European Energy Programme for Recovery
September 2009	:	Project selected for funding by European Commission
May 2010	:	Ministerial decision Dutch funding published
	:	Grant Agreement signed by European Commission and ROAD Project
September 2010	:	Front-End Engineering Design studies Capture Plant completed
		Starting note Environmental Impact Assessment published
June 2011	:	Submitting Environmental Impact Assessment, permit applications
Q3/Q4 2013	:	Final Investment Decision
2017	:	Start of operation CCS chain
2017-2020	:	Demonstration phase CCS chain

2.2 Maasvlakte CCS Project C.V.

The initiating parties of the ROAD project are E.ON Benelux and GDF SUEZ Nederland Energie. Together they constitute the limited partnership Maasvlakte CCS Project C.V.

2.2.1 E.ON Benelux

E.ON Benelux concentrates on the production and supply of electricity and gas to private customers and business customers in the Netherlands and Belgium. E.ON Benelux is primarily an electricity-generating company; the company can trade internationally and has its own professional sales organisation. The company was established in 1941 and since 2000 has been part of E.ON Energie AG. E.ON Benelux's power stations with a total capacity of 1,850 MW are located in the province of South Holland, the economic heart of the Netherlands. The company has approximately 600 employees. E.ON Benelux is based in Rotterdam.

2.2.2 GDF SUEZ Nederland Energie

GDF SUEZ Nederland Energie is a leading player in the Dutch energy market and part of the GDF SUEZ Group. With six state-of-the-art production locations and a total capacity of 5,103 MW GDF SUEZ Nederland Energie is the largest electricity producer in the Netherlands. GDF SUEZ Nederland Energie is a supplier of electricity and gas to both private and business customers and has 1,250 employees.

2.3 Intended Partners

Intended partners of Maasvlakte CCS Project C.V. are GDF SUEZ E&P Nederland for the CO_2 transport and TAQA Energy for the CO_2 injection and the permanent storage under the seabed of the North Sea.

TAQA Energy

TAQA Energy is part of the Abu Dhabi National Energy Company PJSC (TAQA), an energy company that has worldwide interests in power generation, combined heat and water, desalination, upstream oil & gas, pipelines, services and structured finance. TAQA has a workforce of 2,800 employees and is located in Abu Dhabi, The Hague, Michigan, Aberdeen, Calgary and Amsterdam. In addition, TAQA has sustainable partnerships with companies in Africa, the Middle-East, Europe, North-America and India. TAQA is listed at the Abu Dhabi Securities Exchange (ADX).

In the Netherlands, TAQA Energy explores and produces gas and condensates from wells located onshore in the Alkmaar region and offshore in the Dutch North Sea. TAQA also operates a gas storage facility in Alkmaar and has interests in Dutch North Sea pipelines. 200 people work for TAQA directly and indirectly in the Netherlands both onshore and offshore.

GDF SUEZ E&P Nederland

GDF SUEZ E&P Nederland is one of the largest operators in the Dutch sector of the North Sea. With more than thirty production platforms and 300 employees, it is at the basis of the provision of energy to the Netherlands and several other countries.

Since its first successful drilling results in the Dutch North Sea, approximately forty years ago, GDF SUEZ E&P Nederland has grown into a leading operator. It has ample expertise and experience, always chooses the safest option and is continuously working towards the development of new techniques and improved methods. Continuity is ensured through exploration, takeovers and acquisition.

2.4 Financial Contributors

The ROAD project is co-financed by the European Commission within the framework of the European Energy Programme for Recovery (EEPR) and the Government of the Netherlands. ROAD is knowledge partner of the Global CCS Institute and has received financial support in this regard.

In response to the economic crisis, the European Council and the European Parliament adopted the Commission proposal for a European Energy Programme for Recovery (“EEPR”) in July 2009. The EEPR funds projects in the field of gas and electricity infrastructure as well as offshore wind energy and CO_2 capture and storage (CCS). In total 12 CCS projects applied for assistance under the EEPR. In December 2009, the European Commission granted financial assistance to six projects that could make substantial progress with project development in 2010. These projects may receive up to € 1 billion in total under the EEPR.

3. Integrated CCS Chain of ROAD

3.1 Introduction

ROAD is the Rotterdam Opslag and Afvang Demonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the largest integrated Carbon Capture and Storage (CCS) demonstration projects in the world.

3.1.1 Onshore and offshore transport system

The transport system of ROAD consists of a 16 inch pipeline from the E.ON site to the P18-A platform of TAQA in the North Sea at about 25 km from the Maasvlakte in Rotterdam.

Figure 5: 3D visualization of MPP3

After the recommended route as prepared by the Engineering bureau of Rotterdam has been received, ROAD has investigated several alternatives, with the intention to save investment costs.

The proposed route has two Horizontal Direct Drillings HDD’s, one of which (the Maasgeul crossing) requires a very high investment. This is mainly caused by the complexity that occurs when drilling into sea and the related receiving facilities. Further a mud return pipe has to be drilled, to avoid pollution of the sea by mud. On top of that the harbor traffic authorities did not allow any interference with the very heavy traffic in the Maasgeul, which is the only entrance from sea to the harbour of Rotterdam.

The investigated alternative routes show straighter pipe lengths, outweighing the high costs of the directional drillings, and positively influencing the risks associated with long HDD´s. The alternative routes were extensively discussed with the traffic manager of the Rotterdam harbour, and the Water Authority of the North Sea (RWS, Rijkswaterstaat). It turned out that the area to be crossed is an important sand collecting area of Rotterdam (e.g. for the second Maasvlakte) with very steep underwater hills and still in use by RWS and Rotterdam. Furthermore these routes require dredging a trench in the waterway from Rotterdam to the North Sea, which is not favoured by the traffic manager of the harbour. Finally a cost estimate of a dredging company showed that the traffic requirements of the harbour manager of Rotterdam did not support the continuation of the study of these alternative routes.

The pipeline starts at the discharge of the CO_2 product compressor located at the E.ON site in the capture plant. This plant is located adjacent to the new Maasvlakte Power Plant 3 (MPP3), where it receives its feed from the MPP3 (more details on the capture plant can be found in the non-confidential FEED study report of ROAD for the Global CCS Institute).

Figure 6: Footprint available for CCS on MPP3

The 16 inch insulated pipeline starts at the plot of the E.ON power plant at the battery limit valve just before the point where the pipeline is buried. At the E.ON site the pipeline is equipped with a metering station, instrument connections, block valves and a connection for a removable pigging station for inspection of the pipeline condition. The connection for the pigging station is mounted with a pig signal connection, pressure and temperature indicators. The route on the E.ON plot is approximately 400 m long.

From the fence of the E.ON location the pipeline runs in the pipeline corridor of Rotterdam. In this trajectory it crosses a harbor (the Yangtze Harbor) and a waterway (the Maasgeul). After the Maasgeul crossing it runs one meter under seabed of the North Sea to the existing P18-A platform, located in block section P18-A of the Dutch continental shelf.

The onshore pipeline will be insulated with an insulation thickness of 50 mm (PUR/PE) to avoid heat losses from the CO_2 and to provide heat protection to the adjacent pipelines. The pipeline will be trenched in the existing pipeline trajectory at the location and slot as indicated by the Municipality of Rotterdam. The pipeline will have a coverage of one meter, and will be positioned at a distance of 40 cm of its neighbouring pipeline. The Engineering bureau of the Municipality of Rotterdam has determined that the distance between pipelines in the Rotterdam trajectory has to be 40 cm to provide sufficient space for future pipelines

The pipeline is equipped with expansion loops (figure 7) to cope with the thermal and pressure expansion that occurs between the temperature of the pipeline in construction (10 °C, 0 barg) and the design temperature of 80 °C and the design pressure of 140 barg.

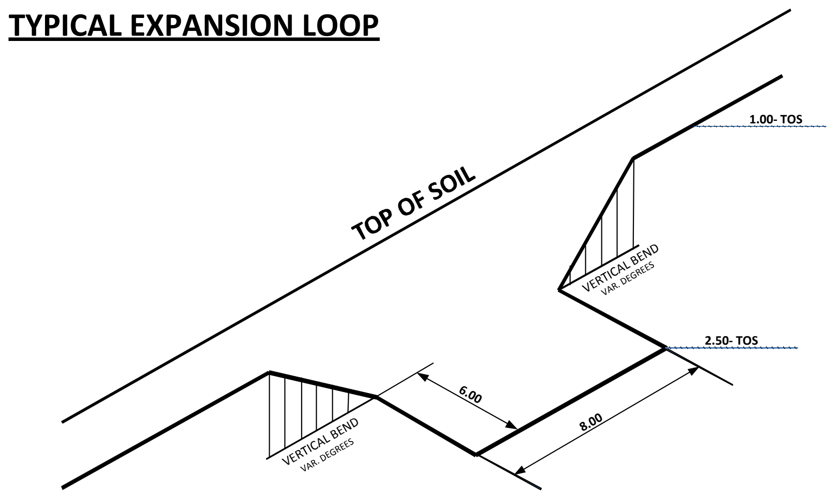


Figure 7: Layout of expansion loops

The expansion loops will be constructed at a lower depth to give space to the next pipeline.

Following the pipeline trajectory the harbor railroad is crossed through a Glass Fibre Reinforced Plastic (GVK) protective pipe of about 36 meters to avoid damage to the railroad in case of leakage. After this, the Australiëweg, another railroad and future pipelines are crossed through a GVK protective pipe of about 48 m length.

From here the pipeline follows the Rotterdam pipeline corridor trajectory over a length of approximately 1,250 m till it leaves the pipeline corridor trajectory to run to the entry point of the directional drilling of the Yangtze harbor. Before the entry point of the Horizontal Directional Drilling (HDD) the pipeline crosses the railroad again through a GVK protective pipe of 26 m in parallel to the existing crossings.

Yangtze Harbor Crossing

The Yangtze harbor is crossed by means of a HDD with an approximate length of 1,425 m. This drilling is equipped as Steel-in-Steel system, which means that the steel medium carrying pipe is constructed in a steel outer pipe. The space between the two pipes is evacuated to establish a sufficient low vacuum to provide insulation. Through this mechanism, the outer pipe stays cooler than the inner pipe and the outer pipe fixes the inner pipe when this inner pipe is expanding due to the temperature and pressure effects. The HDD will run at a depth of -43 m (below Normaal Amsterdams Peil, the reference height for all Dutch height measurements, NAP) to avoid any contact with the sheet piling of the harbor construction and to allow for future increase of the harbor depth. After leaving the Yangtze harbor HDD, the pipeline follows the pipeline corridor trajectory over a distance of approximately 1,200 m to the entry point of the Maasgeul HDD.

The Maasgeul Crossing

The Maasgeul crossing is also constructed as a Steel-in-Steel system. The HDD is approximately 1,625 m long, at a depth of approximately -39 m (below NAP).

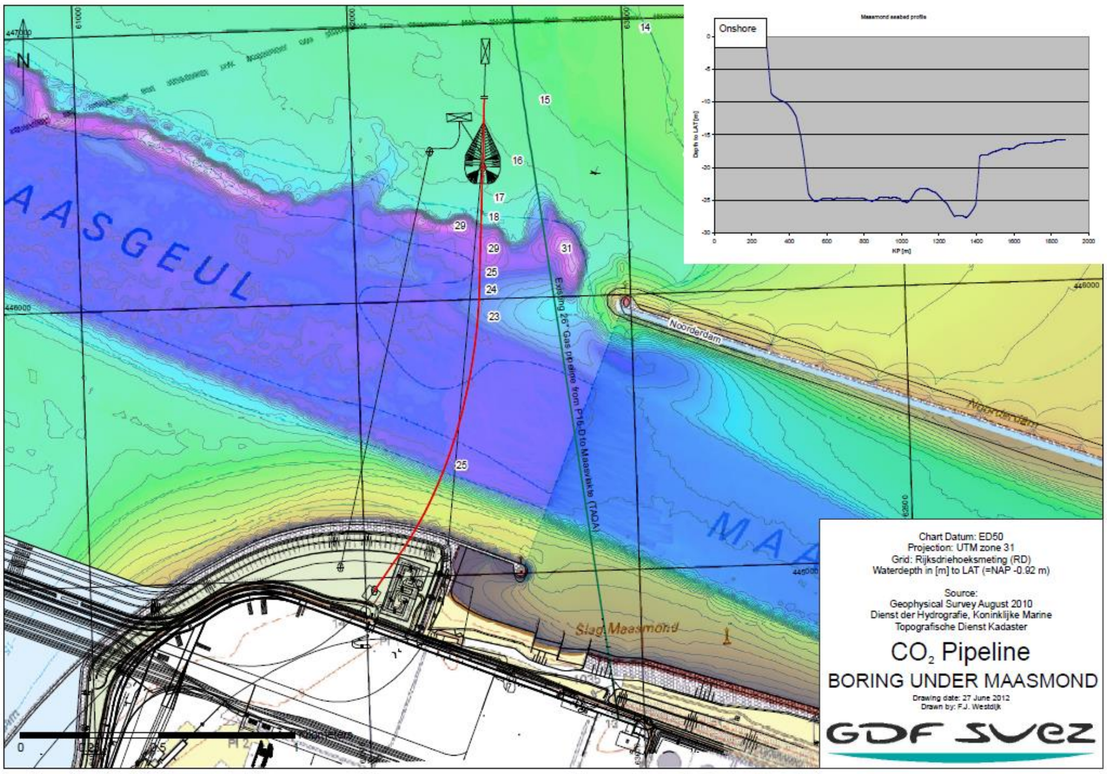


Figure 8: Route and profile of Maasgeul crossing with entrance and exit points

At the offshore point the HDD pipe is picked up by the lay barge of the offshore pipeline contractor. From here the pipeline runs to the platform of TAQA.

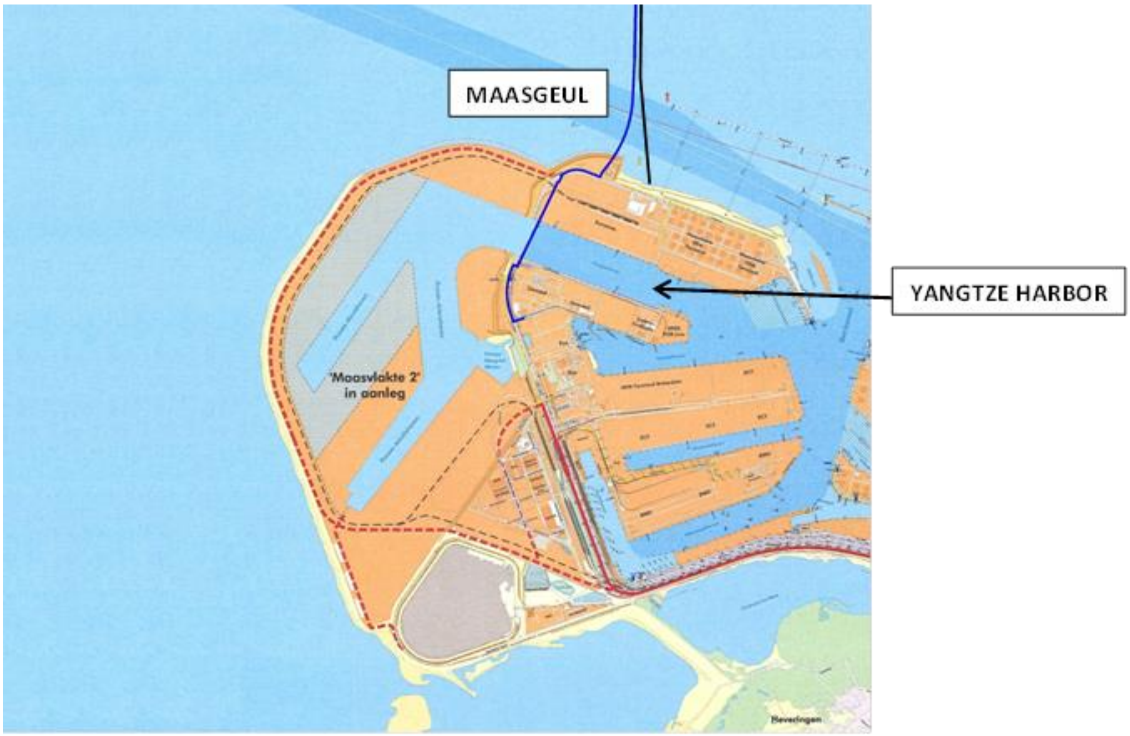


Figure 9: Onshore pipeline route

The Maasgeul is the entrance to the Rotterdam harbor with very heavy traffic. The offshore pipeline route is partially (approximately 9 km) projected parallel to the existing TAQA 26 inch natural gas pipeline at a distance of 85-110 m. The offshore part of the pipeline is insulated with 30 mm PUR/PE.

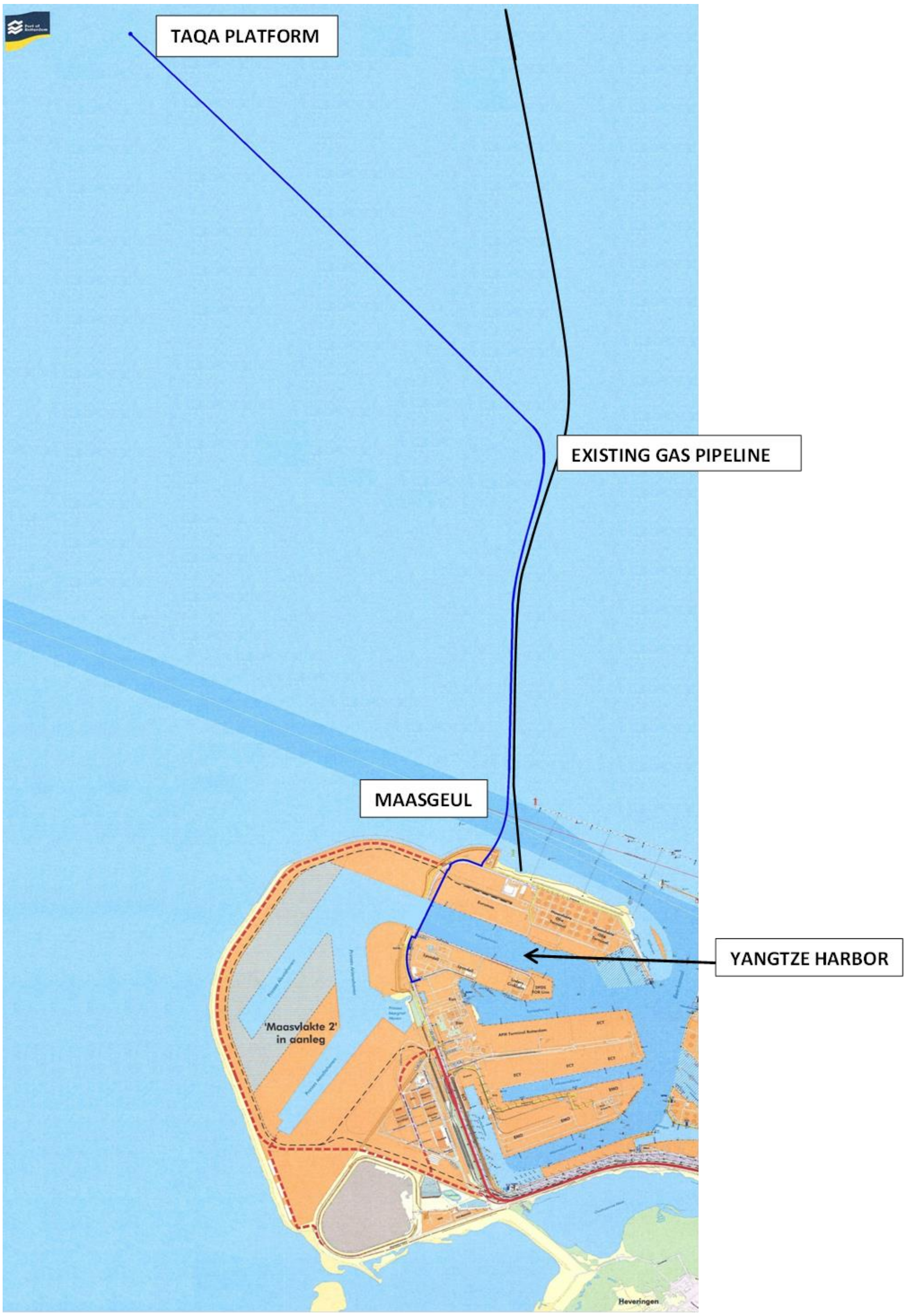


Figure 10: Overview of onshore and offshore pipeline route

The total length of the pipeline route is approximately 25 km and consists of an on-shore section including the two crossings of 5.6 km and an offshore section of approximately 19.4 km.

3.1.2 P18-A Platform of TAQA

The pipeline ends at the existing TAQA (former AMOCO) well protector platform P18-A situated at the North Sea on top of the P18 gas field. The pipeline runs to the deck of the platform where the control and safety equipment is located.

Figure 11: P18-A well protector platform of TAQA

From here the CO_2 will be injected via an existing well (P18-14A2) into a gas field P18-4, which is near the end of its production life and will have ceased production before the start of CO_2 injection.

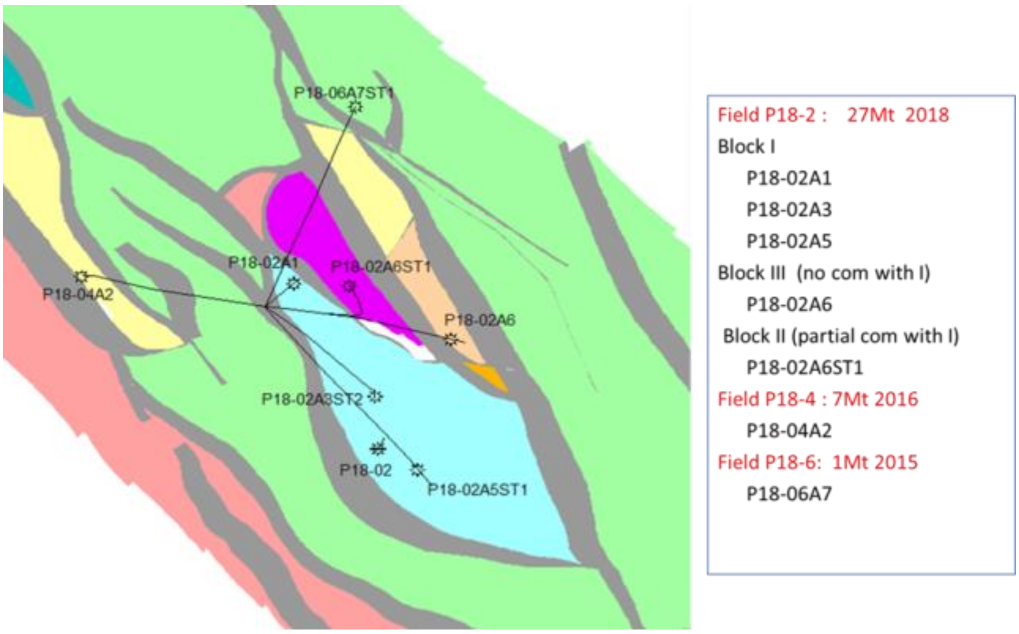


Figure 12: Well locations within P18 where CO_2 will be stored

4. ROAD Design Parameters and Data

4.1 Description of Flow Assurance Study (FAS)

A full Flow Assurance Study (FAS) has been performed to learn the specifics about CO_2 transport and storage. Whereas no exactly comparable CO_2 transport and storage chain has been engineered, the study gave a clear insight in the thermodynamics and flow dynamics of CO_2 in the conditions of the ROAD system.

The FAS has been performed in cooperation with TNO Delft, using the OLGA program. OLGA is a multiphase simulation software package which is widely used in the oil & gas industry for simulating multiphase pipe flows. It incorporates a CO_2 module to reach the highest accuracy in computing CO_2 flows.

The purpose of the FAS was to study the flow regimes of the CO_2 and to determine the operating and boundary conditions of the transport and storage in the ROAD case. The FAS has given ROAD data that allowed ROAD to define the compressor requirements for the CO_2 injection into the P18 field. To reach this, simulations of the entire system were performed, starting from the inlet of the transport pipeline on-shore up to the reservoir.

The simulations were focused on the following primary questions:

- What are the pressure requirements of the compressor for the operating conditions and actual geometries?
- At which conditions of mass flow rate, inlet temperature, reservoir pressure, does two-phase flow occur in the pipeline?
- What type of insulation is required to prevent two phase flow?

More specifically, the FAS has given conditions for:

- Normal operating at the different reservoir pressures
- Normal start-up and shutdown at various reservoir pressures
- Initial start-up
- Emergency shutdown after feed failure onshore
- Emergency shutdown after failure at platform

4.2 Model Description

The transient multiphase flow simulator OLGA (SPT Group versions 7 and higher with different modules) was used as the main simulation tool for the FAS. OLGA uses for the CO_2 single component module and the Span Wagner Equation of State. The Span Wagner equation is a generalised corresponding equation of state that supersedes the earlier equations and is now generally recognised by industry as the most accurate representation of the available experimental pressure, volume and temperature data for CO_2 and its mixtures.

The basis is one dimensional, three-phase fully dynamic simulator including heat transfer. Fluid properties are based on external programs, such as PVTSIM, and are used in OLGA in the form of a matrix in which all properties are tabulated. For use for CO_2 systems, a single component module was added. The main difference between the single component and normal modules is the evaluation concerning phase transitions. In the base OLGA, the pressure, volume and temperature data is supplied to OLGA in the form of tab files. In general for oil and gas applications, the gas-liquid fraction only gradually changes and forms a two-phase envelope that is taken into account in OLGA. For a single component system, the tab file is generated in OLGA using an equation of state, which was setup specifically for pure CO_2.

Figure 13 gives a schematic diagram of the transport system that is used to define the components used in the FAS.

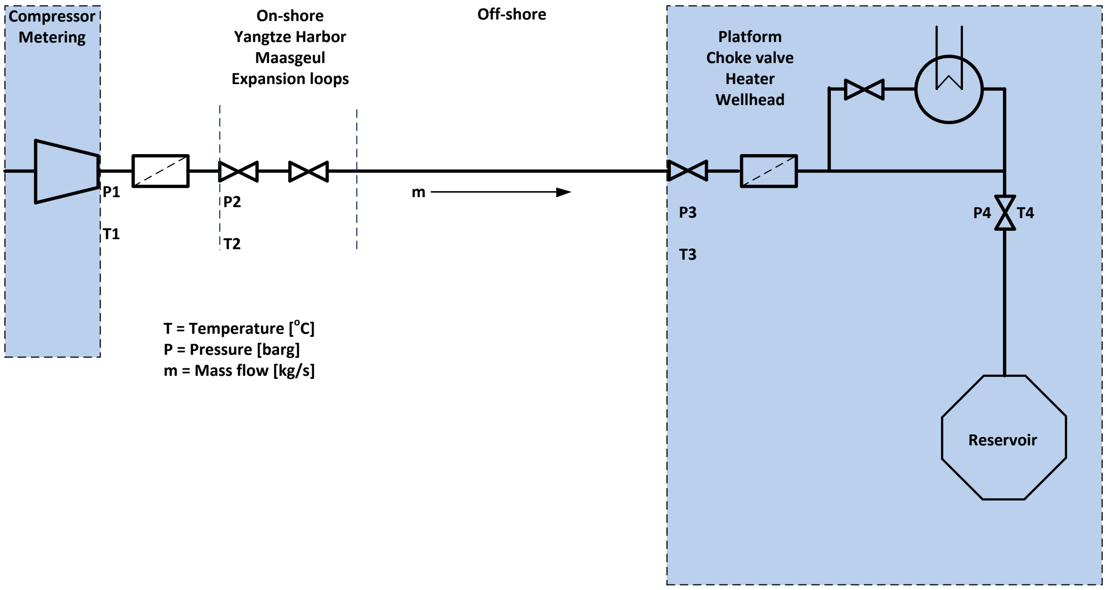


Figure 13: Schematic diagram of the ROAD transport system

4.3 Boundary Conditions for Numerical Simulation

Based on the data from the engineering contractor of the Capture plant and the data of TAQA on the platform and well, the following boundary conditions were given to the OLGA simulations.

4.3.1 CO_2 composition

An analysis was carried out to learn the effects of the CO_2 composition on the thermodynamic data and specific on the condensation behaviour of the CO_2 mixture compared to pure CO_2.

The impurities expected for the ROAD case are, based on the data given by the engineering contractor:

Table: Impurities of CO_2 mixture

N_2	0_2	H_2O	Acetaldehyde	Ar
≤350 ppmv	≤50 ppmw	≤50 ppmv	≤10 ppmv	≤7 ppmv

Effects found were minor and within the range of accuracy for the full range of investigated temperatures and pressures. It was decided to perform the simulations with 100% CO_2.

4.3.2 System temperatures and pressures

Based on equipment already at the platform and in the well the minimum temperature of the wellhead is set at -10 °C. To avoid hydrate formation at the bottom hole the minimum temperature of CO_2 during injection has to stay above 15 °C.

The storage system has to fill the reservoir to approximately 300 barg starting from a pressure of approximately 20 barg. The maximum filling pressure should be under the pressure of the environment, to make sure that the CO_2 will never leave the formation. The above data determine the operating range of the transport system. It is part of the scope of the FAS to advice the operating mode to fulfil these requirements or to suggest modifications.

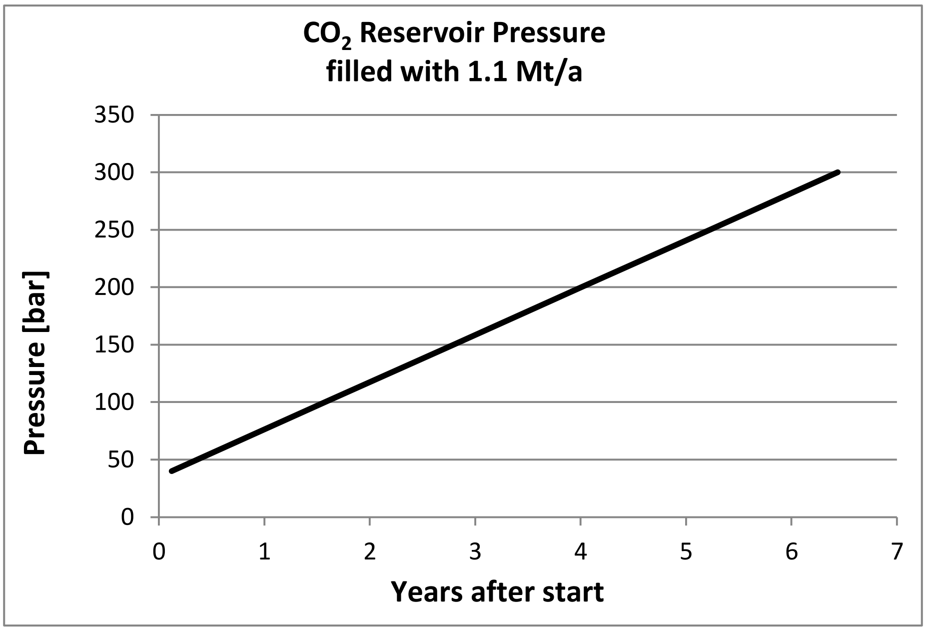


Figure 14: Base scenario for reservoir filling

The maximum operating pressure at the pipeline inlet is determined by the envisaged compressor and initially set at 129 bara. The minimum operating pressure is also set by the compressor and is determined at 40 bara. It is the purpose of the FAS to confirm these boundaries, or to recommend better values.

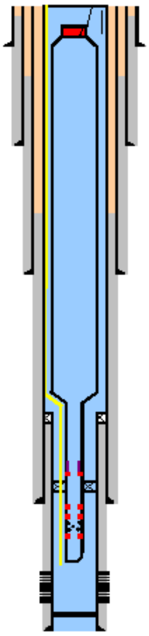
4.3.3 System flow rates

ROAD is designed to deliver 90% capture efficiency on 250 MWe equivalent of the flue gas (following EEPR grant requirements), which equates to a flow rate of 47 kg/s CO_2. With the minimum economical operating flow of the compressor of 40%, this also means a minimum operating flow rate of 18.8 kg/s. Allowing for average operating hours, this equates to approximately 1.1 Mt/a.

4.3.4 Well design

The present well piping will be removed and will be modified for an injection rate of 47 kg/s. At a depth of 122 m the well will be equipped with a subsurface safety valve. The final well design is given in figure 15.

Final completion design 5 1/2" to surface



Rough dimensions:

122 m	ID 4.562 inch
3785 m	ID 6.094 inch
165 m	ID 3.826 inch

Detailed dimensions:

Item	Length [m]	Depth [m]	ID [inch]	ID [mm]
Tubing	114.3	0.0	4.778	121.361
SCSSSV	5.4	114.3	4.562	115.875
X-over	3.0	119.7	4.778	121.361
Tubing	3785.4	122.7	6.094	154.788
X-over	3.0	3908.1	3.826	97.180
Tubing	119.0	3911.1	3.826	97.180
SSD	5.3	4030.1	3.753	95.326
Packer	8.3	4035.4	2.880	73.152
Tubing	10.8	4043.7	3.826	97.180
P gauge	6.0	4054.5	2.922	74.219
P gauge	3.0	4060.5	2.922	74.219
Nipple	1.1	4063.5	2.753	69.926
Perf joint	7.0	4064.5	3.826	97.180
Nipple	1.4	4071.5	2.703	68.656
WEG	0.7	4073.0	2.968	75.387

Figure 15: Final well design

4.3.5 Process system

The system behaves as follows:

The CO_2 is transported by the pressure drop that is generated between the compressor discharge and the reservoir. In every stage of the process at a certain product flow, the only variables available to the operator are the temperature of the CO_2 entering the pipeline in the range of 40-80 °C (limited by cooling water availability) and the pressure in the range 40-125 bara (determined by the compressor design).

The transport and storage is set by the interaction between the static pressure (gain) and the frictional pressure (loss) (determined by density, velocity, static head and pipe length):

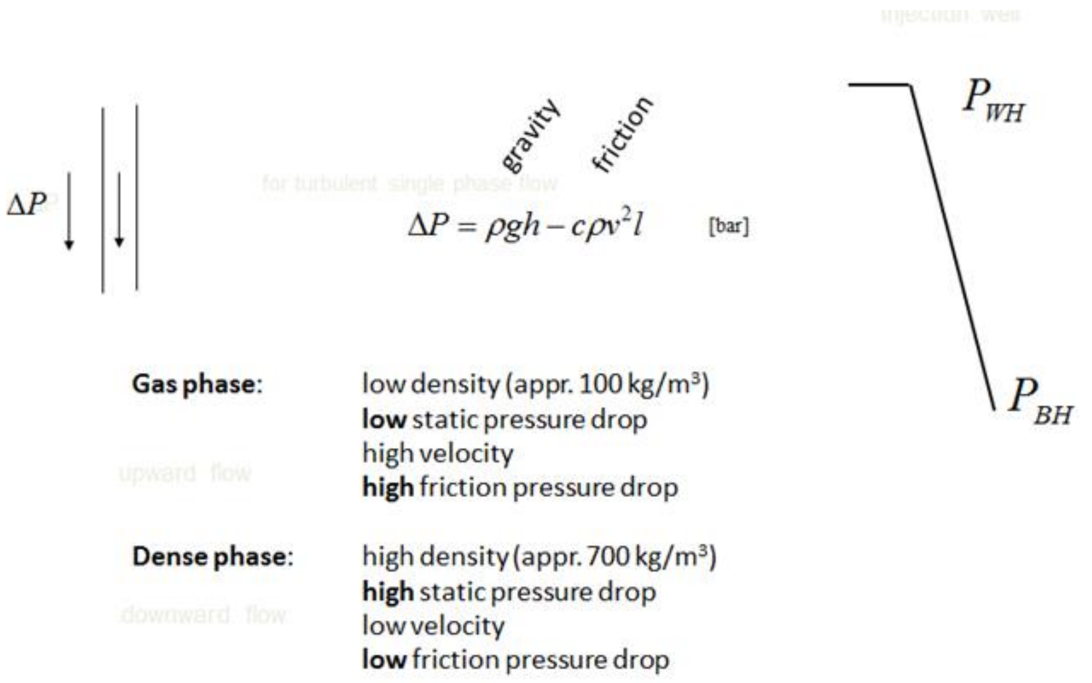


Figure 16: Gravity and friction forces on CO_2 stream into well

It means that the density of the CO_2 is adjusted by its thermo dynamic fluid properties to find the proper equilibrium between above mentioned forces. The thermo dynamic properties can be found in the Mollier diagram of CO_2 (figure 17).

In other words: the compressor has to be able to increase the pressure of the CO_2 above the critical point at the entrance of the well piping at the platform. From that point the density of the CO_2 is such that the CO_2 is 'falling' in the well piping. For the flow into the well till pressures up to 300 barg **no additional compression** is required.

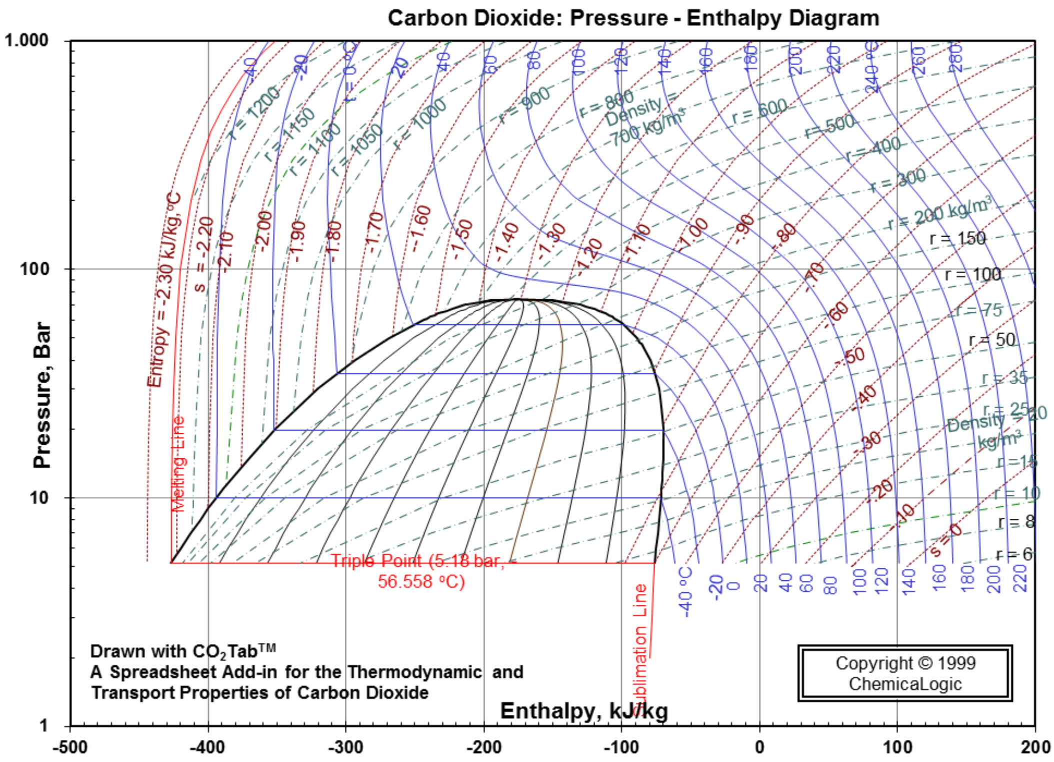


Figure 17: Mollier diagram of CO_2

The simulations have the purpose to investigate if the safe transport and storage is guaranteed within the limitations of the system (boundary conditions).

4.4 Flow Simulations

The simulations performed indicated that at low reservoir pressures the CO_2 has to be transported in gaseous condition. Moreover due to the large pressure drops over the well head the CO_2 could generate very low temperatures, causing risks to the mechanical integrity of the well material.

To compensate for this temperature drop, the CO_2 has to be transported warm in the early stages of the operation. It has been determined that this occurs only in the first half year or so. After that time the CO_2 is – during normal operation – transported in dense phase.

The simulations also indicated that the CO_2 can reach very low temperatures during start-up. It is important that the temperature of the CO_2 is kept at sufficient high level; as to avoid mechanical problems due to cooling and slug formation.

During normal operations the CO_2 can be kept warm by using the heat from the compressor and by the fact that the pipeline is insulated. The CO_2 temperature at the inlet can be lifted to 80 °C by regulating the compressor discharge cooler. However, this solution is not effective at start-up as the pipeline cools off-load.

During the initial stages of the project several possibilities to heat the CO_2 at start-up or prior to start-up were investigated:

- Pipe-in-pipe system with a very high degree of insulation. This configuration is a double steel pipe with vacuum between the two pipes for insulation. This solution was rejected for the very high investment for the 20 km offshore pipeline
- Recycle pipeline to be able to supply the heat up to the platform valves. This solution is also rejected for the high investment costs
- Heating the pipeline by electrical induction, This solution was rejected for the influence of the inherent magnetic fields on ships and vessels in the small water depth in the North Sea
- Heating the CO_2 by a heater on the platform. The heating medium could be natural gas, diesel fuel or electric current. The solution with electric heating was rejected due to the high investment costs of a separate electric cable.

Due to the limited space available on the existing platform there is only room for one heater with a duty of 4 MW. The maximum required heater duty could be as high as 30 MW for a non-insulated pipeline. This requires very high investment costs (extra platform to accommodate heater). Also the operating costs (diesel fuel, natural gas or electricity) for external heating are very high. For this reason the installation of a heater on the platform is rejected, and an operating solution for start-up is investigated in the FAS.

4.4.1 Simulations for normal operating

The results of the simulation, satisfying the boundary conditions, are given in the figures 18 to 20 giving representations of the same results in different parameters:

Figure 18 gives the CO_2 in the phase diagram entering the platform above the critical point (CP: 30.98 bara, 73.77 °C) in the supercritical (dense) phase for different reservoir pressure from 20 to 300 barg (points marked 'wh').

At low reservoir pressure (curve of 20 bar) the friction resistance in the well piping cause the pressure to decrease below the critical region and thus causing vapour flow.

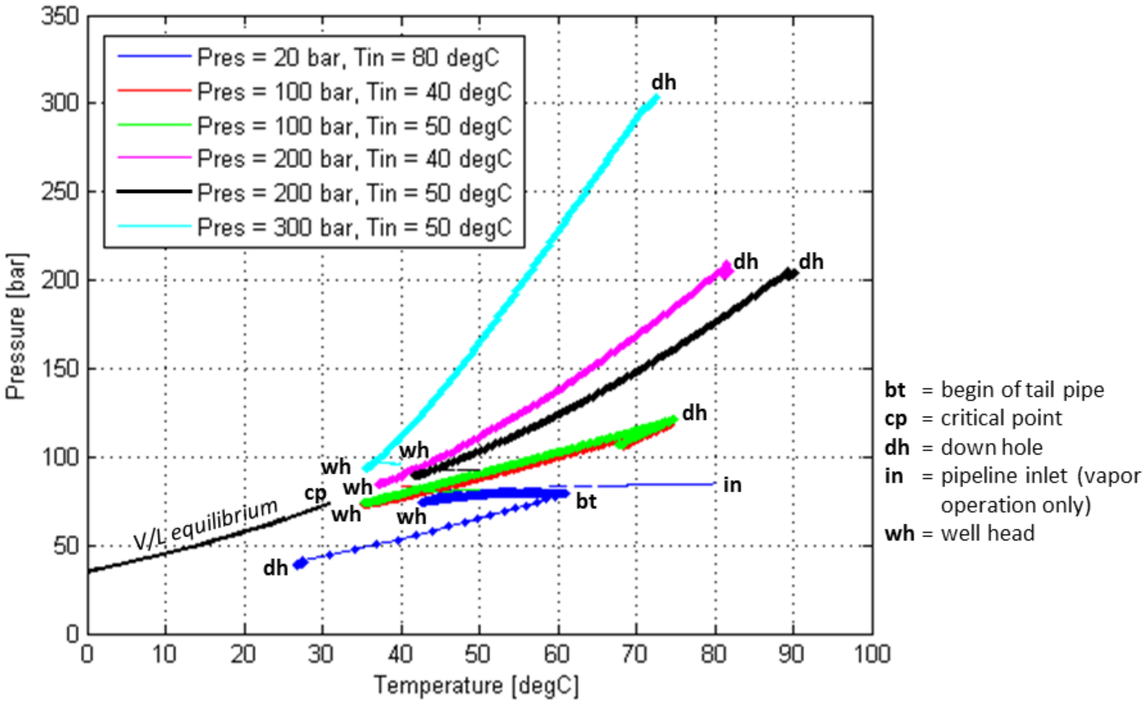


Figure 18: Pressure-Temperature relation for CO_2 in PV diagram

In figure 19 the temperature profile of the CO_2 can be seen as function of the location in the pipeline and the well piping. The high temperature (80 °C) is required to compensate for the temperature drop in the pipeline to avoid too low temperatures after the well head.

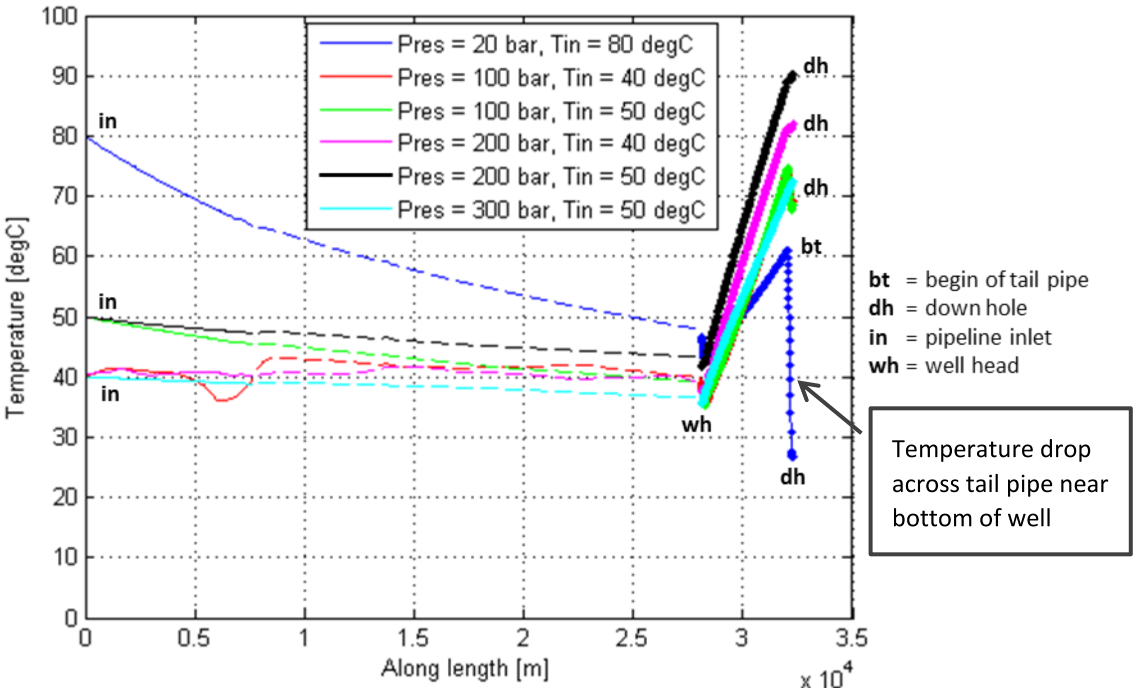


Figure 19: Temperature along the pipeline length

Figure 20 gives the pressure profile as function of the location in the pipeline and the well piping. It shows that at higher reservoir pressures the pressure increases gradually from the well head to the reservoir without intermediate compression. It shows also that at lower reservoir pressure the well head pressure is required to force the gaseous CO_2 down the narrow well tailpipe and into the reservoir.

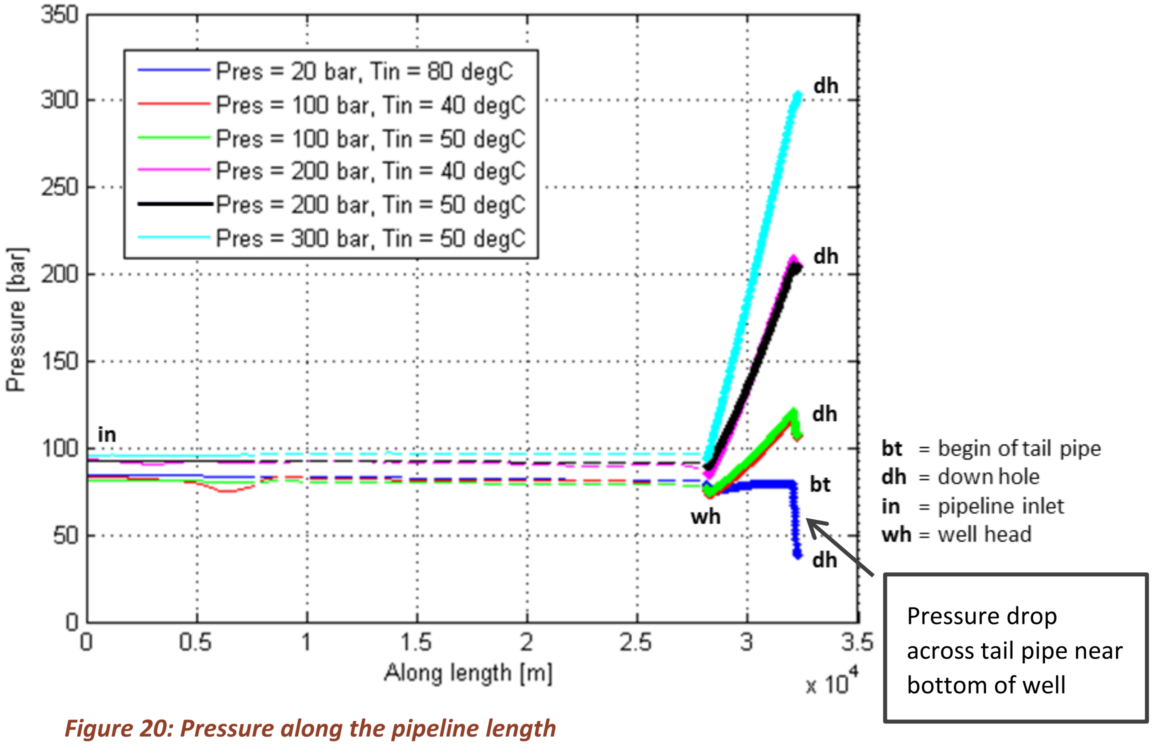


Figure 20: Pressure along the pipeline length

4.4.2 Description of cool-down

Cool-down simulations were performed to learn the cool-down time at various shut-in cases and to determine whether pressurizing the pipeline at a controlled stop would be beneficial. It is expected that frequent starts and stops will occur in the future, possibly on a weekly basis.

Table: Pipeline conditions after shutdown to various pressures

Reservoir pressure [bar]	Pipeline pressure [bar]	Wellhead pressure [bar]	Pipeline condition
20	10.2	10	gas
100	38	45	gas
200	38	45	two phase
300	38	70	two phase

The table above indicates the pipeline condition at controlled shut-down with emptying the pipeline as much as possible to the well (open the wellhead valve till backflow occurs). It shows that it is not possible in all cases to empty the pipeline to single phase. This fact should be taken into account with the subsequent start-up.

When the pipeline is shut-down without emptying the content into the well, in all cases the pipeline content will end up in a two phase condition. This is given in the following table:

Table: Pipeline content after cool-down of a 'full' pipeline

Pipeline fluid pressure [bar]	Pipeline fluid temperature [°C]	Pipeline inlet temperature [°C]	Liquid volume fraction [-]
38.7	4	40	0.13
38.7	4	40	0.31
38.7	4	40	0.75
50.9	15	40	0.08
50.9	15	40	0.82
12	4	80	0 (single phase)

One concludes from these simulations that pressurizing the pipeline before a complete shut-down, does not extend the cool-down time sufficiently to avoid two phase fluid in the pipeline to overcome a shut-down of a weekend (see figure 21).

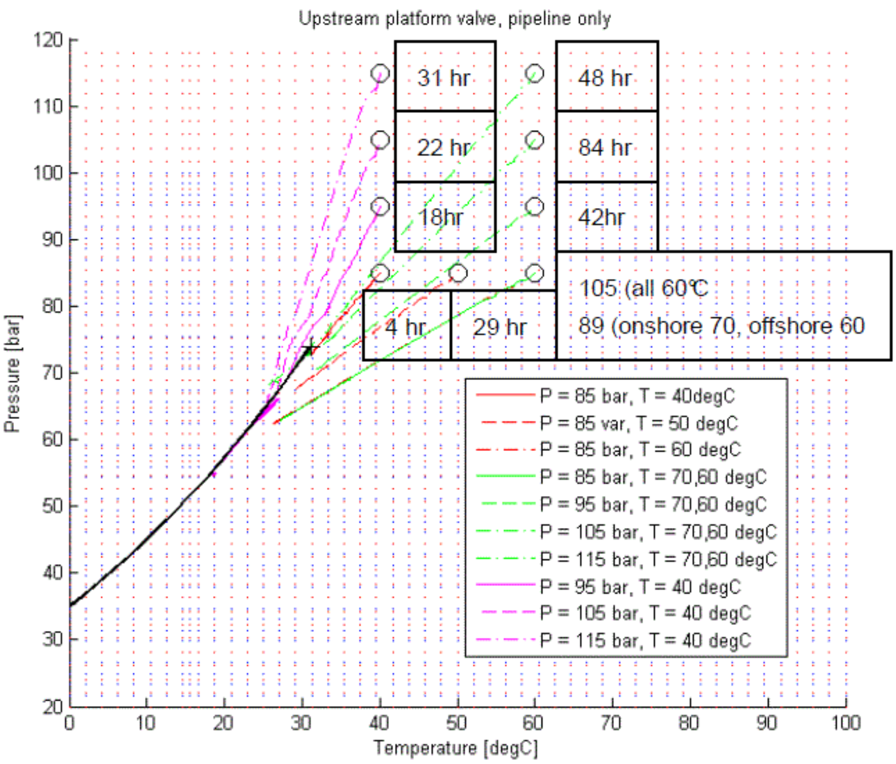


Figure 21: Cool-down times and profiles in phase diagram

4.4.3 Considerations at start-up

From the above one has to conclude that it is very likely that the start-up at high reservoir pressures will have to be executed under two-phase conditions. Since it takes time to heat the pipeline up to sufficient pressure and temperature to reach a single phase status, slugs will occur in the pipeline and liquid CO_2 will be pushed forward from the entrance of the pipeline to the platform.

The engineering parameters and the operating methods should be designed to cope with the forces that can be expected from the two-phase flow.

The behaviour of the liquid flow in the pipeline after start-up with warm gaseous CO_2 from the compressor is simulated, and may be judged in the figure below, which is part of an animation made from the simulations (click here to see animation).

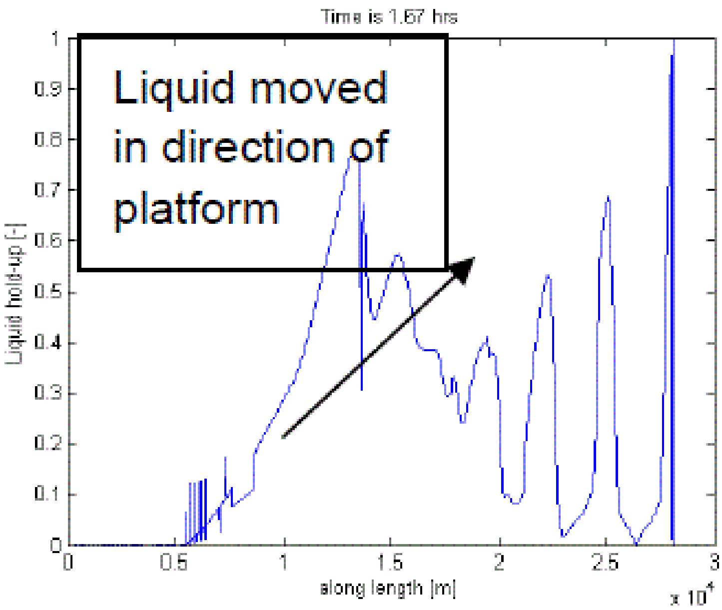


Figure 22: Liquid flow at start-up of 'full' pipeline

At low reservoir pressures the simulations indicated that care should be taken to avoid too low temperatures in the well piping and make sure temperatures do not fall below -10 °C at the well head and +15 °C at the down hole area.

Figure 23 gives the well head and down hole temperatures for various flow rates. One can see that to avoid the low temperature in the early stages of the operation period at low reservoir pressure a reduced flow rate must be applied.

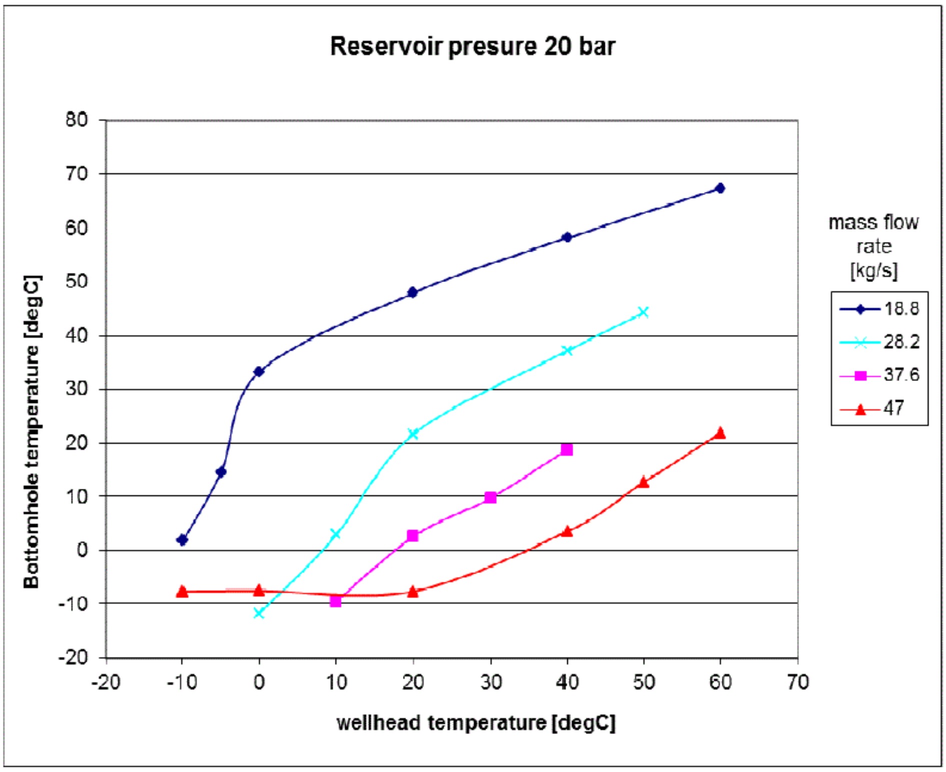


Figure 23: Temperatures at well as function of flow rates

4.4.4 Recommendations of FAS

The various recommendations of the FAS as indicated before are the starting point of the Control and Operating Philosophy as given in the following chapter. The Control and Operating Philosophy is summarized in section 5.5.8.

5. Control and Operating Philosophy

The FAS determined and advised the conditions of temperature, pressure and flow under which the transport of CO_2 can be handled safely. Starting from that advice a description of the control system and the operating parameters have to be made to give the engineering and operating staff the boundaries and explanations for their work. After a description of the control system, a description with points of attention is given of the normal operating, start-up and shut-down modes.

5.1 Process Description

Figure 25 gives an overview of the Basic Control Flowchart CO_2 Compression, Transport & Storage.

The water/CO_2 mixture from the CO_2 stripper is sent to the CO_2 stripper overhead accumulator (D-1), where the gas and liquid phase of the mixture are separated at a pressure of approximately 1.5 bara. The gaseous CO_2 is then fed to the CO_2 product compressor (C-1) and in multiple (8) stages compressed to the required outlet pressure to transport the CO_2 and reach the reservoir on a depth of approximately 3,500 meters. Inside the system of C-1, the CO_2 is dried by a molecular sieve system.

After the compression the CO_2 is cooled by cooling water in heat exchanger E-1 to the required temperature in the range of 40-80 °C, controlled by temperature controller TC-1.

After the CO_2 is compressed to the required outlet pressure (maximum range 40-125 bara), the CO_2 is fed to the platform through a 25 km long subsoil 16 inch pipeline, and then from the platform to the reservoir through a vertical pipe (well pipe).

Basic Control Flowchart CO_2 Compression, Transport & Storage

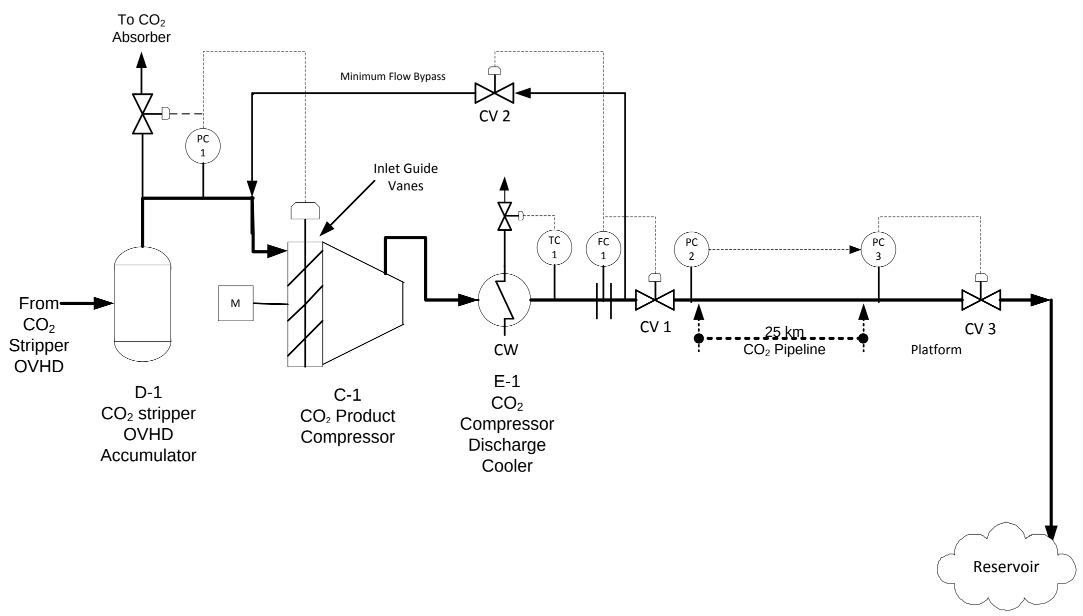


Figure 24: Basic Control Flowchart

5.2 Basic Control Explanation

The compressor C-1 is controlled by the pressure controller (PC-1, Inlet Guide Vanes) at the suction of the compressor. This results in a constant suction pressure and ensures that all the CO_2 produced by the Capture Plant is compressed and transported. The pressure in the reservoir ranges during the operating period from 20 to 300 bara. The discharge pressure of the compressor is determined by the reservoir pressure and the pressure change in between, which depends on density (function of temperature and pressure), static head, mass flow, and the position of the Platform Control Valve.

During this period the condition of state of the CO_2 can be learned from the Mollier diagram, from gas through compressed gas into the dense phase after having reached the critical pressure (73,77 bara).

The mass flow through the compressor and the pipeline is not controlled by this system, but is determined in the Capture Plant by the quantity of CO_2 that is removed from the flue gases.

5.3 Compressor Performance

Figure 26 shows the compressor C-1 is limited in operation by its performance curves.

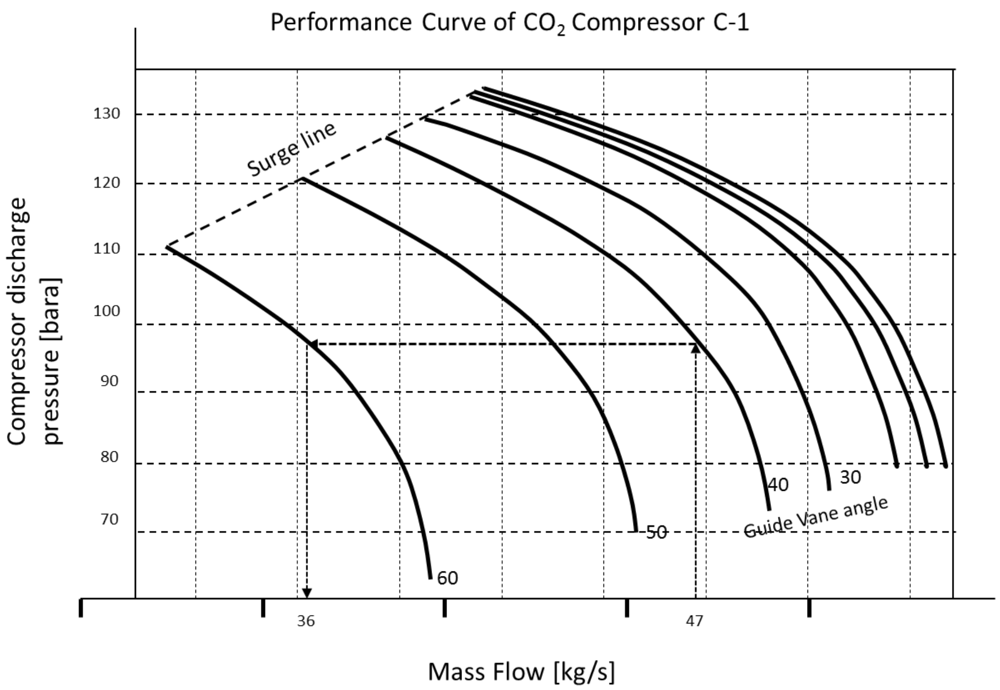


Figure 25: Typical compressor performance curve

Compressor C-1 is equipped with Inlet Guide Vanes that have the ability to control the compressor flow to about 65% of the design value. The design value of C-1 is 47 kg/s. It means that the compressor will reach unstable flow conditions when the flow is below the values indicated on the curve by the lowest Inlet Guide Vanes position (60) and the Surge Line.

In the curve is indicated that the compressor operating at 98 bara and 47 kg/s can only be throttled to about 36 kg/s.

As the unstable flow causes severe vibrations and might damage the compressor after some time, the compressor is equipped with a minimum flow protection (controller FC-1, control valves CV-1 and CV-2). By recirculating a part of the discharge flow after cooling to the suction in case a low flow is occurring or required, the control system maintains sufficient flow through the compressor for stable operation (back in the operating envelop of above given curves). Since this mode of operation causes increased electricity consumption, it is not favourable for extended periods.

5.4 Flow Regimes

The FAS has determined the most suitable flow regimes, pressure and temperature levels to compress, transport and store the CO_2. In the study the following parameters, representing the present status of the transport and storage system, were used:

- Pressure range pipeline entrance 40-125 bara.
- Temperature range pipeline entrance 40-80 °C.
- Pipeline size 16 inch (400 mm), with 50 mm (onshore) and 30 mm (offshore) PUR/PE insulation.
- Mechanical design pressure of pipeline 140 barg.
- Mechanical design temperature of pipeline 80 °C.
- Length of pipeline 25 km, 5 km onshore and 20 km offshore.
- Minimum CO_2 temperature at well head -10 °C.
- Minimum CO_2 temperature at well bottom +15 °C.

The study has shown that in most of the operating conditions, the flow in the pipeline is homogeneous and stable. In the first phase of the operation (for well pressures from 30-73 bara) the CO_2 is transported in the gas phase and the required pipeline entrance temperatures run as indicated in figure 27: initially 80 °C, decreasing to 60 °C.

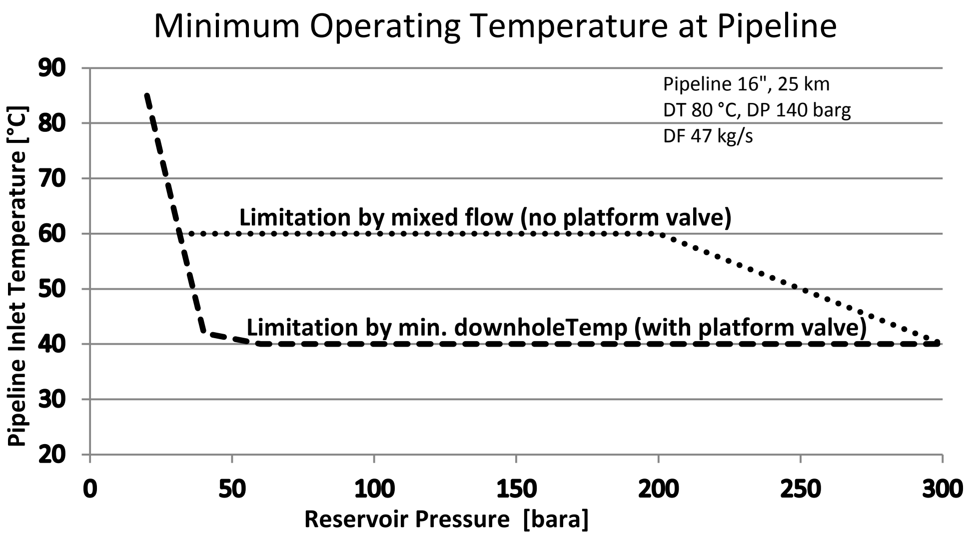


Figure 26: Operating envelopes

The flow in the well piping is homogeneous mixed, where the point of transition from gas to mixed flow is determined by the physical density requirement to reach the equilibrium reservoir pressure at 3.5 km depth.

As the reservoir pressure increases, the density of the CO_2 in the pipeline is increasing into the dense phase with the increasing possibility of two phase flow with the occurrence of slugs.

To avoid the occurrence of slugs the temperature of CO_2 at the pipeline entrance should be limited to a minimum of 60 °C up to 200 bara reservoir pressure, decreasing to 40 °C at a reservoir pressure of 300 bara (figure 27, dotted line).

To lower the required operating pressure and saving considerable amounts of compression energy, the FAS has investigated the use of a control valve at the platform. This platform control valve (CV-3, controlled by PC-2) increases the pipeline pressure without changing the pressure/density regime in the well piping. The increased pipeline pressure forces the CO_2 flow into single phase operation, thus avoiding the occurrence of mixed flow and unstable slugs in the pipeline.

The dashed line in figure 28 indicates the temperatures of this operation. These lower temperatures require less compression power for the transport of the CO_2. The amount of savings of energy can be estimated from figure 28: almost proportional with the area between the two lines.

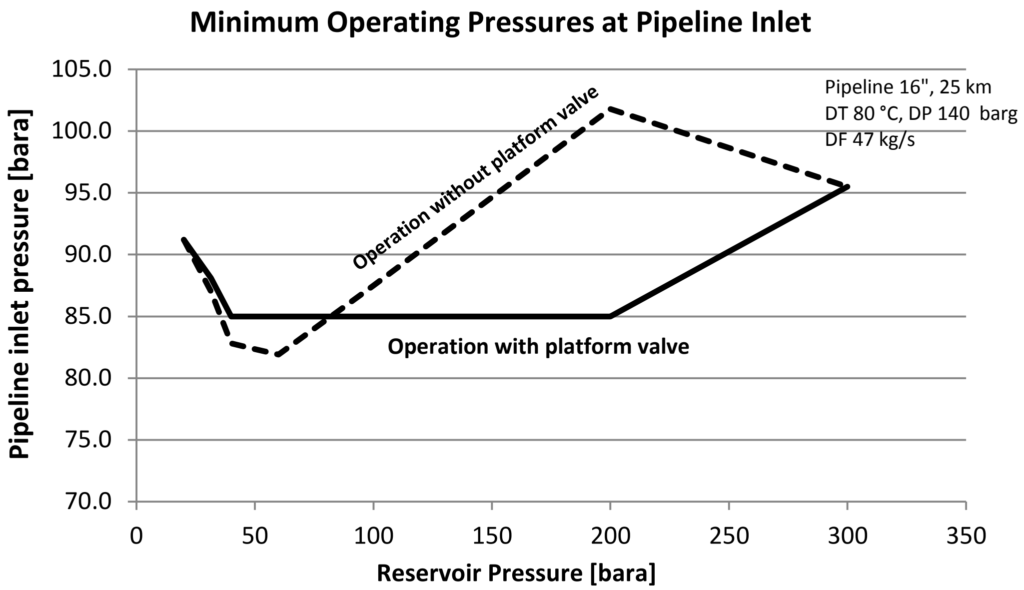


Figure 27: Operating pressures

5.5 Control Philosophy

CO_2 transport system should be operated in the range as indicated in figure 29. This is the condensation of the conclusions of the FAS for normal operating circumstances. Applying a platform control valve (CV-3) saves a considerable amount of energy and will therefore be part of the platform equipment.

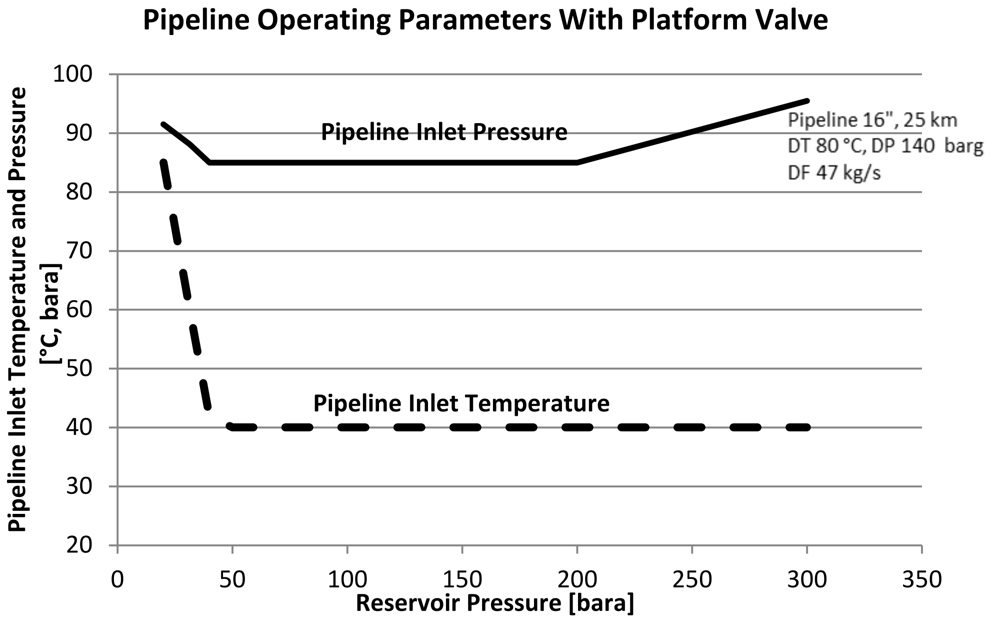


Figure 28: Recommended operating parameters

Apart from a number of monitoring, status and alarm signals, this system has the advantage that only one (1) control signal has to be exchanged between the platform and the central Control Room of MCP: the set point (PC-2 to OC-3) of the Platform Control Valve (CV 3) Controller. This set point should be such, that the pipeline inlet pressure (PC-2) is as given in the upper curve of figure 29, and will be 86.5 bara from approximately 40-200 bara reservoir pressure.

5.5.1 Non-steady state operations

Since the operation of the MPP3 Power plant and the CO_2 capture and storage system of ROAD are governed by economic parameters, while staying within the boundaries of the demonstration contract, it is likely that frequent start-ups and shutdowns are necessary.

It is not predictable how often these non-steady state operations will occur, but because of their nature they need special attention. In the Flow Assurance Study much attention is paid to these phenomena.

The non-steady state operations can be divided into:

1. Initial start-up
2. Planned start-up after planned shutdown
3. Planned shutdown
4. Planned start-up after a non-planned (emergency) shutdown
    - By Capture Plant operation
    - By Platform operation

5.5.2 Initial and normal start-up

The initial start-up commences after the commissioning of the pipeline, at the availability of CO_2 gas from the MCP plant. It is assumed that the compressor section and the pipeline are filled with dry nitrogen or dry air to a minimum pressure of 5 barg (high enough to prevent any wet air or water from entering the pipeline).

A detailed initial start-up plan will be made in close cooperation between the MCP staff and the pipeline commissioning contractor. However, it will follow the basic rules as indicated below:

As soon as the MCP plant delivers dry CO_2 on spec, it is entered into the pipeline at the minimum pressure and flow possible by the compressor train. Since it is difficult to know when the pipeline is sufficiently free of inert gas, it is recommended to have the pig launcher in operation and a pig mounted to provide a physical separation between the O_2/N_2 content of the pipeline and the entering CO_2 from the compressor. The speed of purging will be determined by the maximum pig speed, the quantity of air that can pass the platform vent, and the maximum noise level that can be accepted at the platform vent.

When the pig is received at the platform, the CO_2 can be forwarded to the CV-3 (Platform Control Valve) and the Choke valve. As soon as the CO_2 has reached CV-3 the pressure in the pipeline is increased to a value required for a planned start-up at low reservoir pressure. Care must be taken to ensure that the pressure of the pipeline does not drop to a point where wet air can enter.

The quantity of inert gas to be vented can be calculated from the actual volume of the pipeline (approximately 2,700 actual m^3), being approximately 16,200 Nm^3 at 5 barg.

5.5.3 Planned start-up after planned shutdown

Basically there are the following two modes of start-up:

The first mode is to pressurize the pipeline by the full compressor flow to a pressure where single phase is obtained in the pipeline. After the single phase is reached in the pipeline, open the valves at the platform to allow the gas to enter the well piping. This method is described in the FAS report. However, the disadvantage of this method is the fact that the flow in the well piping tail part will reach very high velocities, possibly causing vibrations and damage to this pipe.

The flow in the well piping and the temperatures in the well head and in the tail end of the well piping should be closely monitored to avoid low temperatures (due to the pressure drop at the well entrance) and to avoid (very) high flow in the tail end of the well piping. The temperature in the well head material should not drop below -10 °C to avoid brittleness, and preferably the temperature at the tail end of the well piping should stay above approximately +15 °C to avoid the formation of hydrates. In practice it might be impossible to avoid temperatures below +15 °C in the tail end, but possibly formed hydrate will dissolve as soon as the pressure and/or temperature rise again.

The second, more preferable, mode is to open the well pressure control valve CV-3 as soon as the pressure in the pipeline has reached the well head pressure. The pipeline may then still contain a considerable amount of liquid CO_2.

It has been calculated that liquid slugs in the feed to the CV-3 (Platform Control Valve) do not cause dangerous (too high) pressure spikes. The maximum being approximately 115 bara, sufficiently below the mechanical design pressure of the system of 140 barg. It is therefore possible to apply this knowledge to the start-up procedure as given below.

5.5.4 Preferred start-up procedure

Open CV-3 as soon as the pipeline pressure has reached the point of the downstream pressure of CV-3. The flow to the platform may then contain liquid slugs, but due to the low flow rate it is not expected that these slugs will do any harm. Due to the low pressure drop over the valve, a minimal quantity will flow into the well piping, causing a limited temperature drop. It also will cause low flow rates in the well piping and no vibration and/or erosion problems in the down hole well piping. As the pipeline pressure rises, the flow rate into the well will increase.

The operation staff should carefully monitor the temperatures and pressures both at the well head and the down hole piping, and the pressure drop over CV-3. When liquid slugs will pass CV-3, fluctuations in pressure and flow rate are expected. While in general CV-3 should be fully open in this start-up phase, it may be necessary to restrict the flow rate to avoid back flow, low temperatures or to moderate pressure/flow rate fluctuations. As soon as the pipeline content is in a single phase, the flow rates and pressures can be adjusted to values as indicated in figure 29.

5.5.5 Planned shutdown

The vapour and liquid CO_2 content in the pipeline before the start-up is depending on the shut-off temperature of the pipeline and the amount of cool-down the pipeline has encountered.

One can calculate that the quantity of CO_2 in the pipeline is about 475 tonnes at cooling down from 85 bara and 80 °C and about 950 tonnes at cooling down from 85 bara and 40 °C. Figure 30 shows the vapour weight fractions at a cooled down temperature of 4 °C for these cases (0.22 and 0.58).

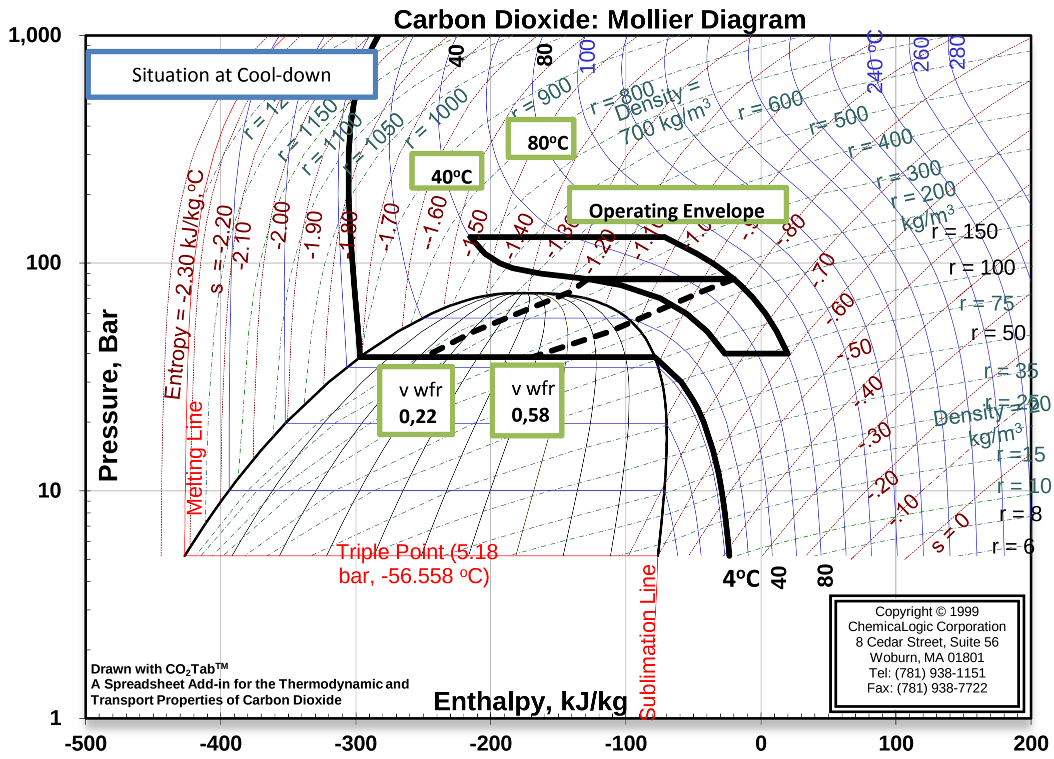


Figure 29: Pipeline contents at cool-down

The start-up will be faster when the pipeline is pressurized and heated-up with less content. It is therefore advantageous to heat the pipeline content to the highest possible temperature (close to 80 °C) before the planned shutdown. The shutdown temperature is determined by the operating staff and is mainly dependent on the available time for the heating-up and the available time to the following start-up. One should bear in mind that it will cost at least 4-6 hours to heat the pipeline content from approximately 35 to 70 °C in reality.

After the pipeline has reached the most favourable conditions for the shut-down and cool-down, the compressor discharge valve is closed first.

The pipeline is emptied into the well as long as a positive flow is maintained into the well. When the pipeline pressure is close to the wellhead pressure, the CV-3 should be closed (the pipeline pressure at the platform should always stay above the wellhead pressure to avoid backflow).

Care should be taken that no backflow from the well is occurring.

The pipeline is further cooling down, under close attention of the operating staff. This shutdown mode prevents the occurrence of very high velocities in the well piping and consequentially avoiding vibrations during start-up.

5.5.6 Planned start-up after emergency shutdowns by capture plant operation

At any emergency in the Capture Plant the compressor discharge valve is closed to protect the contents of the pipeline. When this occurs, the pipeline is emptied as described under paragraph 5.5.5 Planned shut-down.

However, since this shut-down is not preceded by a controlled heating up of the pipeline, the pipeline may contain more CO_2 than in the normal Planned Shut-down, and the start–up after the cool-down may take longer. The operating staff should watch the start-up after the cool-down closely to avoid too much flow into the well with consequentially too high velocities (low pressure drop across CV-3).

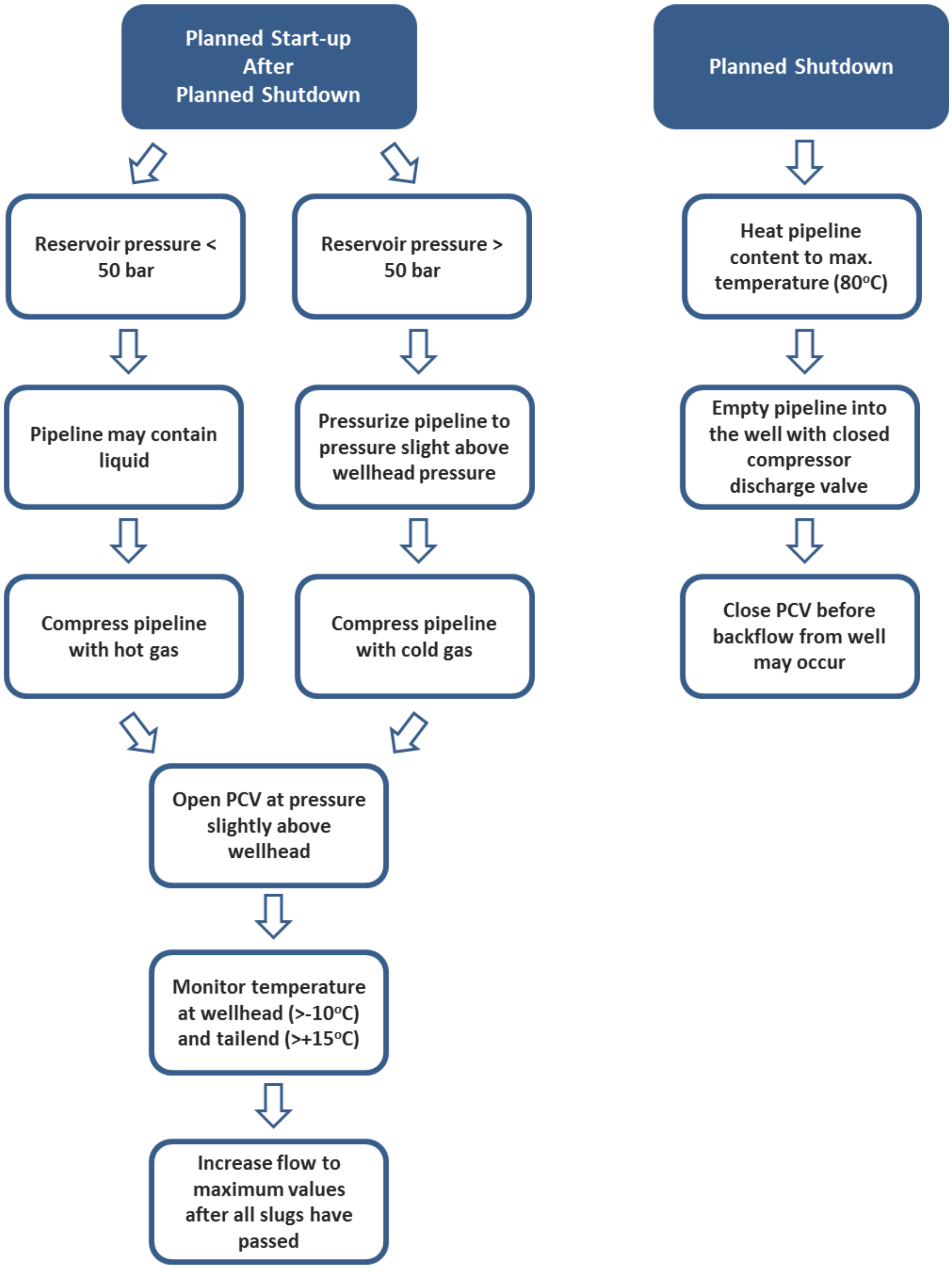
5.5.7 Planned start-up after non-planned shutdown by the platform operation

Any emergency on the platform will cause CV-3 valve to be closed by the emergency system, or the operator of the platform. In this case the content of the pipeline cannot be emptied into the well and the pipeline/capture plant operators have to decide how to continue, depending on the expected repair time of the emergency reason.

1. When it is expected that repair of the emergency is done within a reasonable time, say some hours, it is recommended to continue to operate the Capture Plant by discharging the CO_2 into the pipeline at the maximum possible temperature (80 °C). This causes the pipeline content to heat up and prolongs the cool-down time. After the restoration of the Platform operation, the CV-3 is opened at a low flow rate level according the Normal start-up procedure of paragraph 5.5.2. When the slugs are passed, CV-3 can be opened at the normal flow rate.
2. When it is expected that repair of the emergency reason will take a considerable time, it is recommended to start a shutdown of the Capture plant to save utilities. After closing the compressor discharge valve, the pipeline is cooled down, and the Capture Plant is restarted after the repair of the emergency reason, following the Normal start-up procedure of paragraph 5.5.2.

5.5.8 Summary of the control and operating philosophy

The various start-up and shutdown modes are summarized in the following scheme.



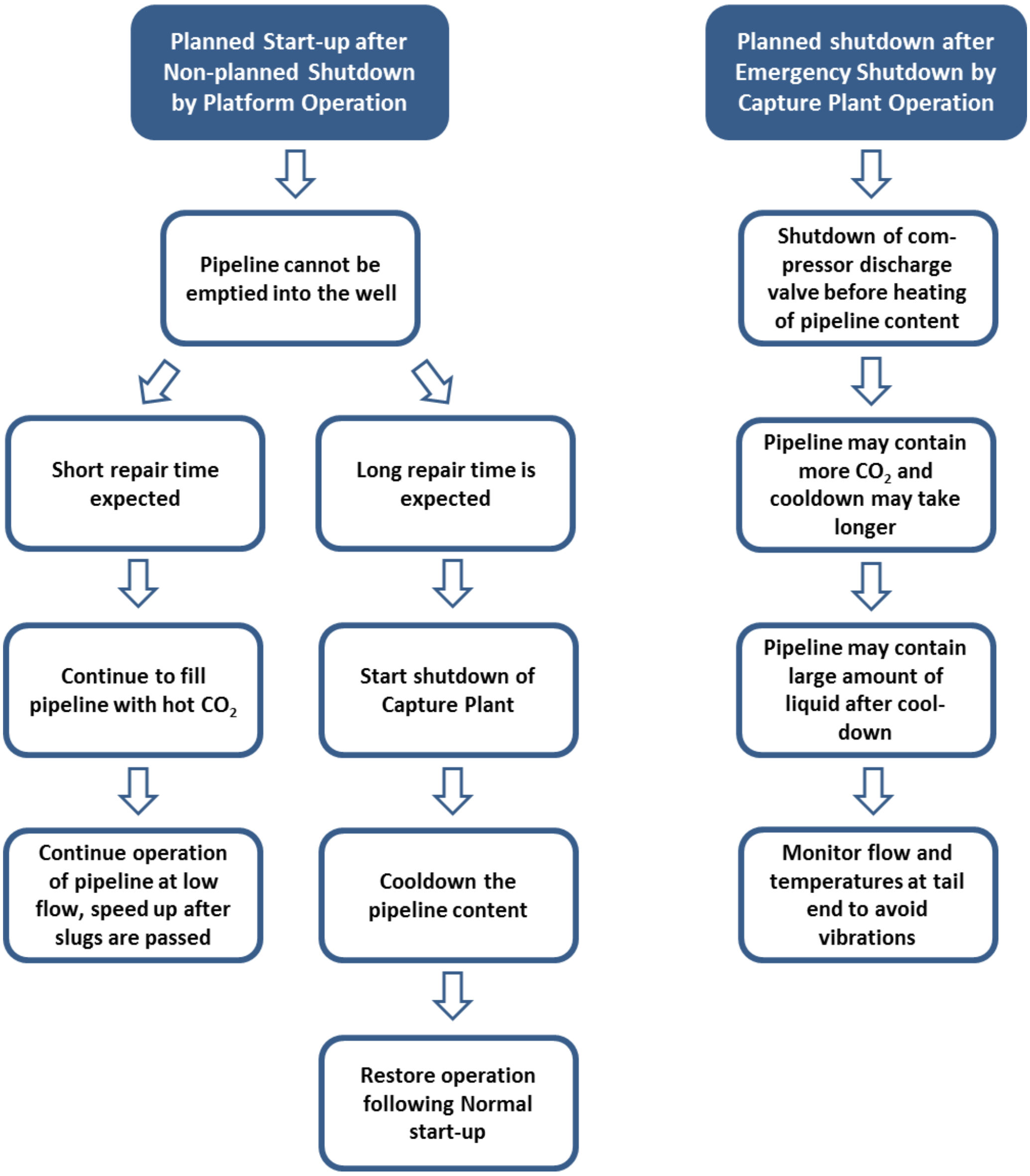


Figure 30: Summary of the control and operating philosophy

6. Conclusions and Recommendations

Although it has not been practiced before, the FAS has clearly shown that filling a reservoir of (very) low pressure to an end pressure of 300 bar is in practice possible, but one has to study the behaviour of the CO_2 gas in all its thermodynamic aspects with the parameters of the physical configuration of the transport system.

The FAS has resulted in safe procedures for the following operating cases:

- Initial and normal start-up
- Planned start-up after a planned shutdown
- Planned shutdown
- Planned start-up after a non-planned (emergency) shutdown
    - By capture plant operation
    - By platform operation

In this special report it has been pointed out that the CO_2 should be transported warm at low reservoir pressures and start-up to minimize low temperatures and slugs. Slugs may still occur at start-up, but will not do any harm, as long as the simulations are aimed to determine the maximum forces in the pipeline and the platform piping, and the design and construction of the equipment on the platform are resistant to minor slugs.

It is recommended to further investigate the possibility that the CO_2 can be injected without any heating, making sure that the slugs can be handled in the well piping. This will mean that transporting CO_2 to low pressure fields is also feasible over larger distances and in pipelines without insulation. The operation of systems with supercritical CO_2 is very uncommon. The complexity of the system demands a long operating learning time with close attention of the operating staff.