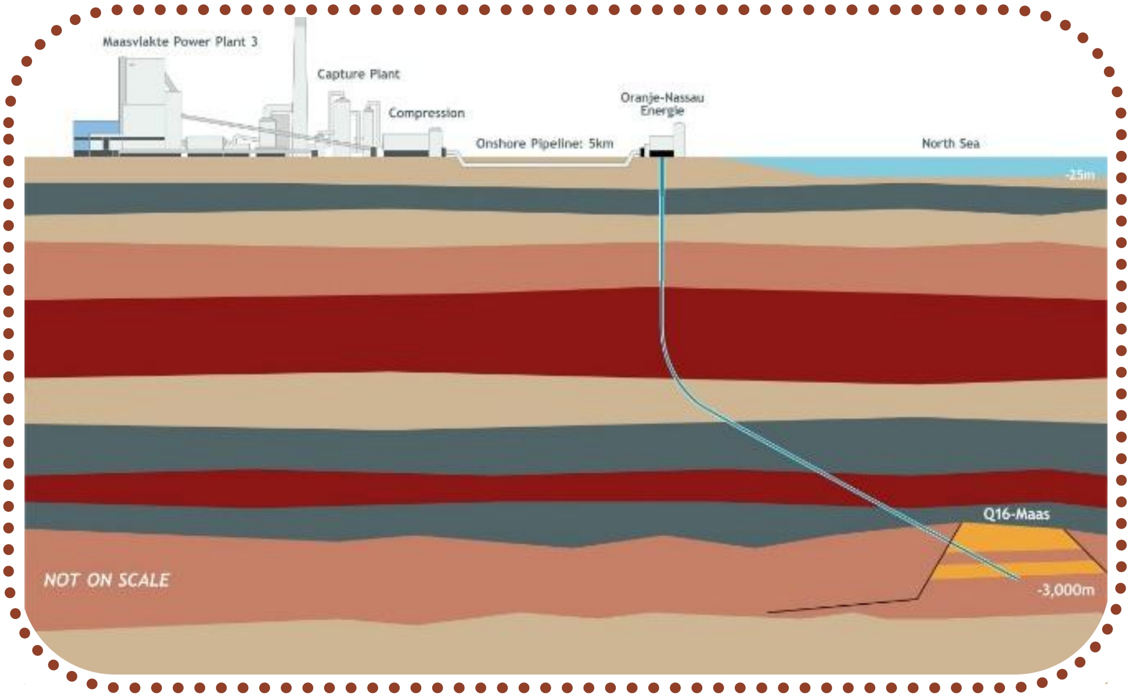
Public Close-Out Report Transport

Rotterdam Opslag en Afvang Demonstratieproject



Maasvlakte CCS Project C.V.

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Close-Out Report 3 of 11: Transport

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3	***Transport***	***Technical report covering CO_2 pipeline transport.***
4	CO_2 Storage	Both technical and commercial aspects of CO_2 storage for ROAD. Subsurface work required to demonstrate permanent storage is described.
5	Risk Management	The risk management approach used by ROAD.
6	Permitting and Regulation	Description of the regulatory and permitting framework and process for the ROAD project, including required changes to regulations.
7	Governance and Compliance	Company structure and governance for Maasvlakte CCS Project C.V., the joint venture undertaking the ROAD Project
8	Project Costs and Funding	A presentation of the projected economics of the project, with both projected income and costs.
9	Finance and Control	Description of the financial and control systems, including the costs incurred and grants claimed.
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Management Summary

Project Summary

This public close-out report summarises the technical development, design and lessons learnt on transport of CO_2 from the CCS demonstration project "ROAD". The ROAD Project (Rotterdam Opslag en Afvang Demonstratieproject) was one of the largest integrated carbon capture and storage (CCS) projects in the world, aiming to install carbon capture on a coal-fired power station in Rotterdam and store the CO_2 in an empty off-shore gas-field.

The project ran from 2009 to 2017. The developer was Maasvlakte CCS Project, a joint venture between Uniper (formerly E.ON) and Engie (formerly Electrabel and GDF Suez), with financial support from the EU EEPR program, the Dutch Government, the Port of Rotterdam and the Global CCS Institute.

In the first phase of the project, 2009-2012, the project was developed to Final Investment Decision (FID) based on using the TAQA P18-4 gas-field as the CO_2 storage location. This required a pipeline of approximately 25km from the capture location (Uniper's coal-fired Maasvlakte Power Plant – MPP3), about 5km onshore and 20km off-shore.

Unfortunately, the collapse in the carbon price undermined the original business case, and in 2012 a positive FID was not economically possible. The project then entered a "slow-mode" in which activities focused on reducing the funding gap, either by reducing costs or by securing new funding. In late 2014, a possible new funding structure was identified, and explored in 2015 and 2016. This included additional grants for operation and cost reductions. The cost reduction that could be successfully applied was to change storage sink to Q16-Maas, operated by Oranje-Nassau Energie (ONE). This smaller field was much closer, with only a 6 km pipeline required. This resulted in a remobilization of the project late in 2016, and development of the new scheme. However, in mid 2017 work was again halted, and formally stopped in November 2017.

Scope of this report

This report describes the technical work on the CO_2 transport systems for both phases of the project. In depth work to FID standard was completed for pipeline transport to storage in the P18-4 gas reservoir from 2009-2012. Scenarios were then studied for connection to the OCAP system to supply CO_2 to greenhouses in South Holland, and finally the pipeline from MPP3 to Q16-Maas was specified and designed to allow scope for future connections to both P18-4 and OCAP.

Main Highlights / Lessons Learnt

In all cases, safe and practical designs to transport and store the CO_2 were developed. The preferred designs were different for the two transport systems due to the different characteristics of the storage fields (off-shore and very low pressure for P18-4, on-shore for Q16-Maas). This gives rise to the general lesson that the optimized transport system will depend on the storage location and characteristics.

A particular challenge for P18-4 was designing for the initial period with very low reservoir pressure, and the associated risk that Joule-Thompson cooling of the CO_2 at pressure drops would give very low temperatures in parts of the system. Extensive modelling with OLGA was required to identify a robust and low cost solution. During these early operations, the CO_2 is to be transported warm using heat from the compression, which resulted in the addition of insulation to the pipeline.

Continued modelling showed that two phase flow in the pipeline is difficult to avoid during transient operations (restart after shutdown), but that the slugs have a moderate nature and the equipment can be designed to accommodate the transient slugs. A task for future work is to assess whether in fact these slugs can be tolerated in steady-state operation. This would allow the pipeline to slide pressure with the reservoir, and remove the need for heating or insulation on the pipeline altogether.

The routing of the pipeline followed conventional practice for pipeline development, with the on-shore pipeline to follow an existing pipeline corridor across Port of Rotterdam land. The only CO_2-specific highlight concerned the safety case because data for CO_2 leakage from pipelines is limited and there was no pre-existing precident on estimating the risks. The initial calculation of the QRA (Quantified Risk Assessment), including risk to neighbouring pipelines, was challenged. A second more conservative calculation was used for the final permit application to ensure the calculation was a worst case based on current knowledge. In the event, this did not lead to a change of the pipeline design or routing.

For storage at Q16-Maas, final compression at the injector well was feasible due to the on-shore industrial location. This allowed the transport conditions to be selected independently of the injection requirements. Transport conditions matched to the OCAP system (which supplies CO_2 to greenhouses) were selected to allow for future CO_2 supply to and from the OCAP system at low cost.

1. Introduction

1.1 Background

The ROAD project was one of the leading European CCS Projects from 2010 to 2017. During that time, a great deal of project development and engineering work was completed, including full design and procurement to allow a possible FID at end 2011 or early 2012.

This report is one of a set of public "close-out" reports written after the formal decision to terminate the project was made in September 2017. The report aims to summarise the technical work done on the CO_2 transport system during the full duration of the project, and to highlight lessons learnt. The objective is to give future CCS project developers, and knowledge institutes, the maximum opportunity to use the knowledge gained and lessons learnt by the ROAD project team.

This brief introduction to the "Close-out Report Transport" gives a general description of the overall project, including the history of its development, and describes the scope and structure of the remaining report, which focuses on the technical design of the transport pipeline system. This should enable readers to quickly locate information of relevance to them in this report.

1.2 General Project Description

The ROAD Project is the Rotterdam Opslag and Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project) which ran from 2009 to 2017, and was one of the leading integrated Carbon Capture and Storage (CCS) demonstration projects in the world.

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

ROAD is a joint project initiated in 2009 by E.ON Benelux and Electrabel Nederland (now Uniper Benelux and Engie Nederland). Together they formed the joint venture Maasvlakte CCS Project C.V. which was the project developer. The ROAD Project is co-financed by the European Commission (EC) within the framework of the European Energy Programme for Recovery (EEPR) and the Government of the Netherlands. The grants amount to € 180 million from the EC and € 150 million from the government of the Netherlands. In addition, the Global CCS Institute is knowledge sharing partner of ROAD and has given a financial support of € 4,3 million to the project. The Port of Rotterdam also agreed to support the project through investment in the CO_2 pipeline.

In the first phase of the project, 2009-2012, the project was developed to final investment decision (FID) based on using the P18-4 gas-field operated by TAQA as the CO_2 storage location. This required a pipeline of approximately 25km from the capture location (Uniper's coal-fired Maasvlakte Power Plant – MPP3), about 5km onshore and 20km off-shore.

Unfortunately, the collapse in the carbon price undermined the original business case, and in 2012 a positive FID was not economically possible. The project then entered a "slow-mode" in which activities focused on reducing the funding gap, either by reducing costs or by securing new funding. In late 2014 a possible new funding structure was identified, and explored in 2015 and 2016. This included additional grants for operation and cost reductions. The cost reduction that could be successfully applied was to change storage sink to a newly developed field, Q16-Maas, operated by Oranje-Nassau Energie (ONE). This smaller field was much closer, with only a 6 km pipeline required. This resulted in a remobilization of the project late in 2016, and development of the new scheme. However, in mid 2017 work was again halted, and the grant formally terminated in November 2017.

The ROAD project design applied post combustion technology to capture the CO_2 from the flue gases of a new 1,069 MWe coal-fired power plant (Maasvlakte Power Plant 3, “MPP3”) in the port and industrial area of Rotterdam.

The capture unit has a design capacity of 250 MWe equivalent. During the operational phase of the project, approximately 1.1 megatons of CO_2 per year would be capture and stored, with a full-load flow of 47kg/s (169 t/h) of CO_2. For transport and storage two alternatives were developed as described above: storage in the P18-4 reservoir operated by TAQA; and storage in the Q16-Maas reservoir operated by Oranje-Nassau Energie.

After a competitive FEED process, Fluor was selected as the supplier for the capture technology in early 2011. The plant was fully engineered, and long lead items contracted for, ready for an FID in early 2012. All the necessary permitting was completed, with a permit for the capture plant being granted in 2012. Following the delay to the project, an updated design was developed with Fluor in 2017 incorporating lessons learnt from research and development in the intervening years, changes to the MPP3 site, and the impact of the changes to the transport and storage system. A revision to the permit was under development when the project was halted.

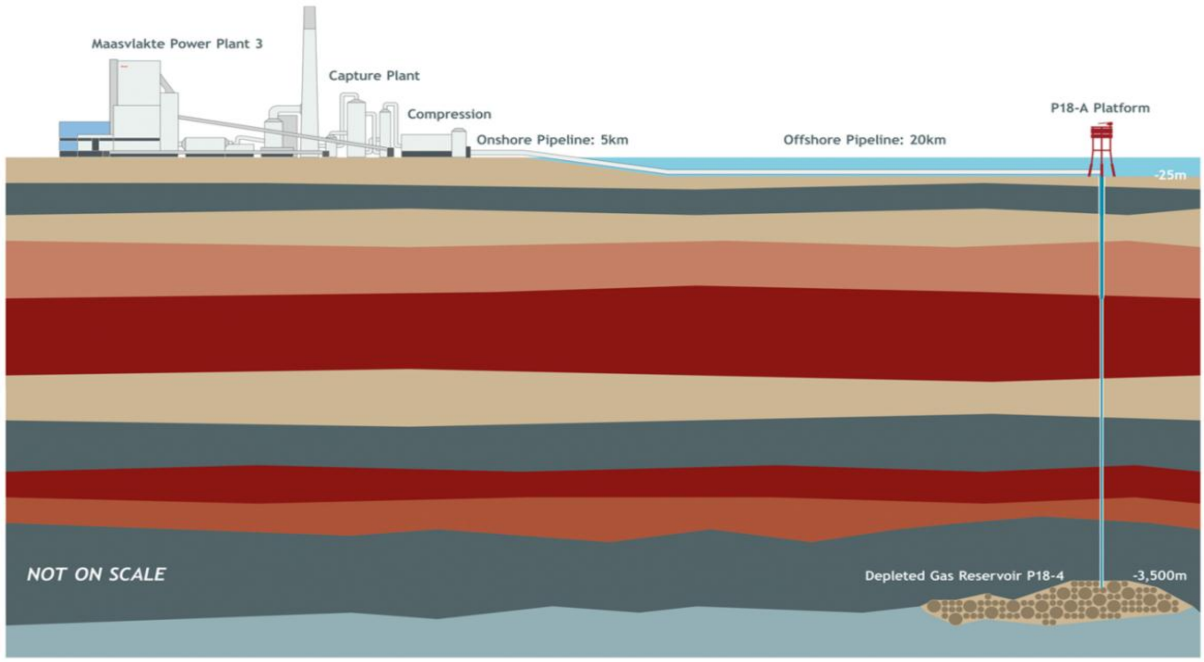
For Storage in P18-4

From the capture unit the CO_2 would be compressed and transported through a pipeline: 5 kilometers over land and about 20 kilometers across the seabed to the P18-A platform in the North Sea. The pipeline has a transport capacity of around 5 million tonnes per year. It is designed for a maximum pressure of 140 bar and a maximum temperature of 80 °C. The CO_2 would be injected from the platform P18-A into depleted gas reservoir P18-4. The estimated storage capacity of reservoir P18-4 is approximately 8 million tonnes. Figure 1.1 shows the schematic illustration of this.

P18-4 is part of the P18 block which also includes the larger P18-2 and also a small field, P18-6. These depleted gas reservoirs are about 3.5 km below the seabed under the North Sea about 20km from the Dutch coastline, and have a combined CO_2 storage capacity of around 35 Mt.

The ROAD Project with storage in P18-4 was fully developed for FID at the end of 2011, including all engineering, regulatory and permit requirements. A CO_2 storage permit was granted in 2013, the first such permit in Europe. Unfortunately, a positive FID was not possible due to funding problems, and in 2012 technical project development on P18-4 was halted.

Figure 1.1: Schematic overview of the ROAD Project using storage in P18-4



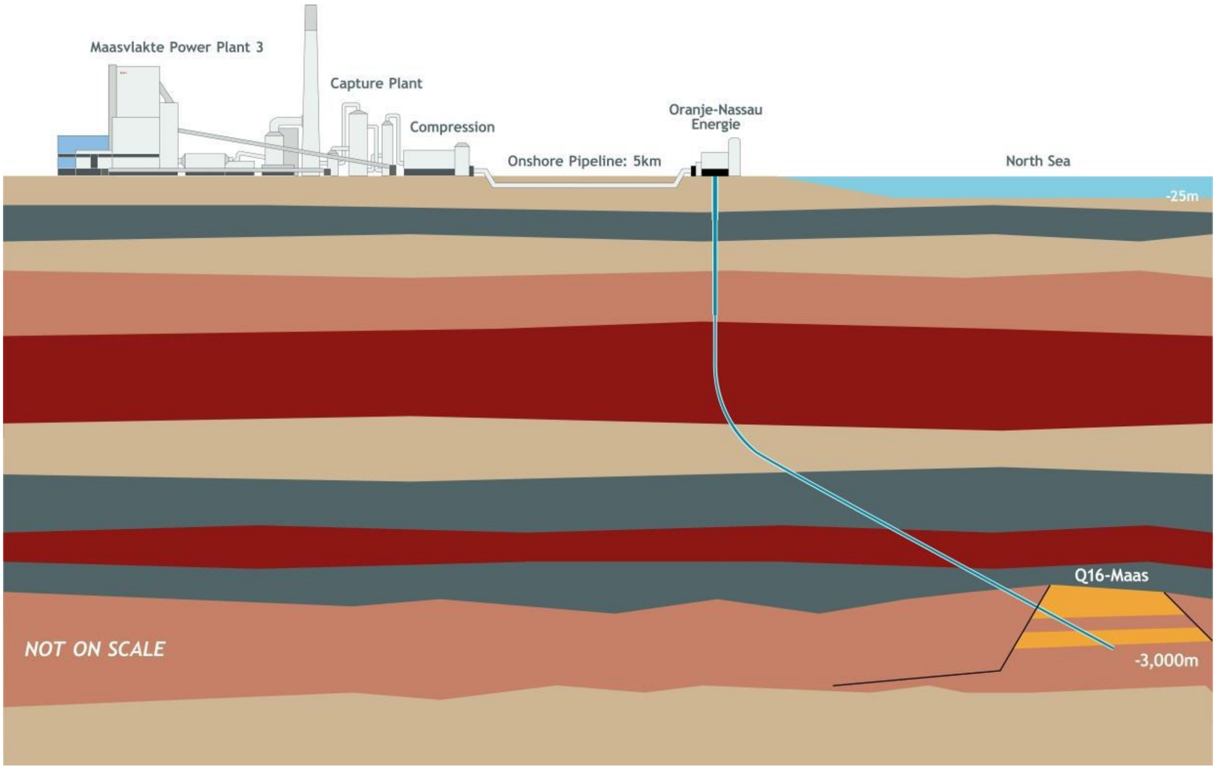
For Storage in Q16-Maas

From the capture unit the CO_2 would be compressed and transported through a pipeline over land to the current ONE-production site Q16-Maas (Figure 1.2). The selected pipeline design would have a transport capacity of in excess of 6Mt/year. It was designed for a maximum pressure of 40 bar although in the first phase operation at 20 bar was planned. Final compression to injection pressure (around 80 bar) would be at the injection site.

The Q16-Maas reservoir is located just off-shore from the Maasvlakte, and is reached by a long-reach well, drilled from on-shore. The well is about 5km long, and travels approximately 3km down to reach the reservoir depth, and 3 km horizontally (off-shore) to reach the reservoir location. The reservoir is relatively new (production started in 2014) and was not due to finish production until 2022. Therefore this scheme involved the drilling of a second well to accelerate gas production and so allow CO_2 injection to start in 2020. This second well would also allow co-production of modest amounts of condensate (and possibly natural gas) during CO_2 injection. The estimated storage capacity of reservoir Q16-Maas is between 2 and 4 million tonnes.

This reservoir was identified as a possible storage location only at the end of 2014, with project development running through 2015-2017. Due to funding uncertainties, the work focused on feasibility, cost estimation and concept design to the level required for permitting. Therefore a lower level of detail is available for this storage location, compared to P18-4. It should also be noted that unexpected water production was experienced from Q16-Maas in 2016, leading Oranje-Nassau Energie to issue a revised reservoir model and production plan in May 2017. Since this was only shortly before the ROAD work was halted, the ROAD plans for Q16-Maas were not fully amended to reflect this new production data.

Figure 1.2: Schematic overview of the ROAD Project using storage in Q16-Maas



1.3 Scope and Structure of this Report

This report summarises the work done on the pipeline transport systems for both the P18-4 and Q16-Maas storage options.

Section 2 covers the concept design phase in 2010, in which P18-4 was selected as the preferred storage location and the basic options for the transport design were explored and selected.

Section 3 covers the detailed design and engineering phase. The first parts cover the main issues for the P18-4 design. This includes:

- Flow assurance work of the transport system to ensure the low pressures in the P18-4 reservoir can be handled without low temperatures occurring in the pipeline or storage system.
- Route engineering for both on-shore and off-shore parts.
- Alternative pipeline routes that were considered.

Subsequently, section 4 summarises a study to look at possible connection to the existing OCAP CO_2 pipeline in Rotterdam, which supplies CO_2 to greenhouses, and it the describes the engineering development of the transport pipeline to Q16-Maas, developed from 2015 to 2016.

Where more detailed technical reports can be published or are already published, these are also referenced in the report and attached in an Annex.

There are lessons learnt throughout the report. Key lessons that we think are transferrable to other projects have been brought together in the Management Summary under the heading "Main Highlights / Lessons Learnt".

2. Conceptual Design Phase

After the overall decision to collect, clean, transport and store a portion of the CO_2 exhaust of the Uniper Maasvlakte Power plant MPP3 has been made, the Conceptual Design of the system was initiated. Initial, high level system design focused on the capture and storage systems. Following that, Genesis was asked in 2010 to develop the transport conceptual design in more detail.

The studies were performed for a capacity of the onshore facilities of 1.1 million tons CO_2 per annum. This is equivalent to a design CO_2 rate of 47 kg/s design with the power station operating at 6500 hours per annum at full load.

These studies indicated that the objective to transport and store CO_2 in the gas field P-18 is feasible under the following important conditions.

1. The pipeline diameter has to be chosen 16" to avoid high power costs for the transport of the required future expansion peak flow of 5 million tons per annum.
2. In the beginning of the storage cycle, when the well is at low pressure, the CO_2 stream needs to be heated to avoid a high temperature drop caused by the pressure drop over the throttle valve. This might result in:
    a. cooling down the material of the well piping to a temperature under the minimum mechanical design temperature. A lower temperature will result in brittle material and can cause damage of the well piping,
    b. formation of solid hydrates which may plug the well piping temporarily. This process is reversible and the hydrates will decompose at higher temperature.

Genesis proposed to heat the CO_2 at the platform to avoid high pressure drops in the pipeline by transporting warm CO_2. During this study the following three heater options were considered:

1. Electrical heater (requires an electric cable from onshore)
2. Gas fired heater (requires an operating gas production of the platform)
3. Compact Diesel fired heater (requires a diesel oil storage tank)

The report gives CAPEX cost estimates for the above mentioned alternatives, which led to the conclusion that a direct diesel fired heater was the preferred solution. More details on this work is given in Section 5 of the Close-out Report on Storage. However, the ROAD team has in a later stage decided, considering the short period of time the heating of the CO_2 will be required (only at the early phase of storage when the well pressure is low), not to install a heater and so reduce the CAPEX. Instead, it was decided to transport warm CO_2 through an insulated pipeline. The concern Genesis raised of high pressure drops in the pipeline due to warm CO_2 did not turn out to be a problem due to the sizing of the pipeline to allow for future expansion.

The conceptual design phase was closed with the following preliminary conclusions that were to be detailed and confirmed in the design and engineering phase:

1. The assumed set-up and layout of the system:
    a. Power plant-Capture plant- CO_2 compression- CO_2 pipeline transport- CO_2 storage in gas field
    b. P-18A is feasible and can be evaluated further
2. Pipeline final route has to be determined in the next phase but runs preliminary from the Maasvlakte MPP3 Power plant in the Rotterdam pipeline corridor, under the Yangtze canal, following the pipeline corridor, under the Maasmond harbor inlet, from the Maasmond harbor inlet under the North Sea bottom to the Taqa P-18A platform.
3. The pipeline will have the following properties:

- Insulated carbon steel,
- Mechanical design pressure 130 bar ga.,
- Mechanical design temperature 80°C
- Size 16”
- Total length appr. 25 km, 20 km off shore, 5 km onshore

The overall system can be reviewed in the PFD and P&I drawings listed below and attached in the Annexes:

- Ref 1: Process Flow Diagram Overall PFD 16” CO_2 pipeline, E.ON plant to TAQA Offshore Ref 1251674_001_Rv00
- Ref 2: Piping and Instrumentation Diagram CO_2 pipeline section Ref 1251663_001_Rv00
- Ref 3: Piping and Instrumentation Diagram P18A Platform Modifications Connection with subsea pipeline Ref 1250699_001_Rv06
- Ref 4: Piping and Instrumentation Diagram P18A Platform Modifications Connection with P18-4A well head Ref 1250700_001_Rv04
- Ref 5: Piping and Instrumentation Diagram List of Symbols Ref 1251299_001_Rv01

3. Detailed Design and Engineering Phase (P18-4)

3.1 Onshore Route

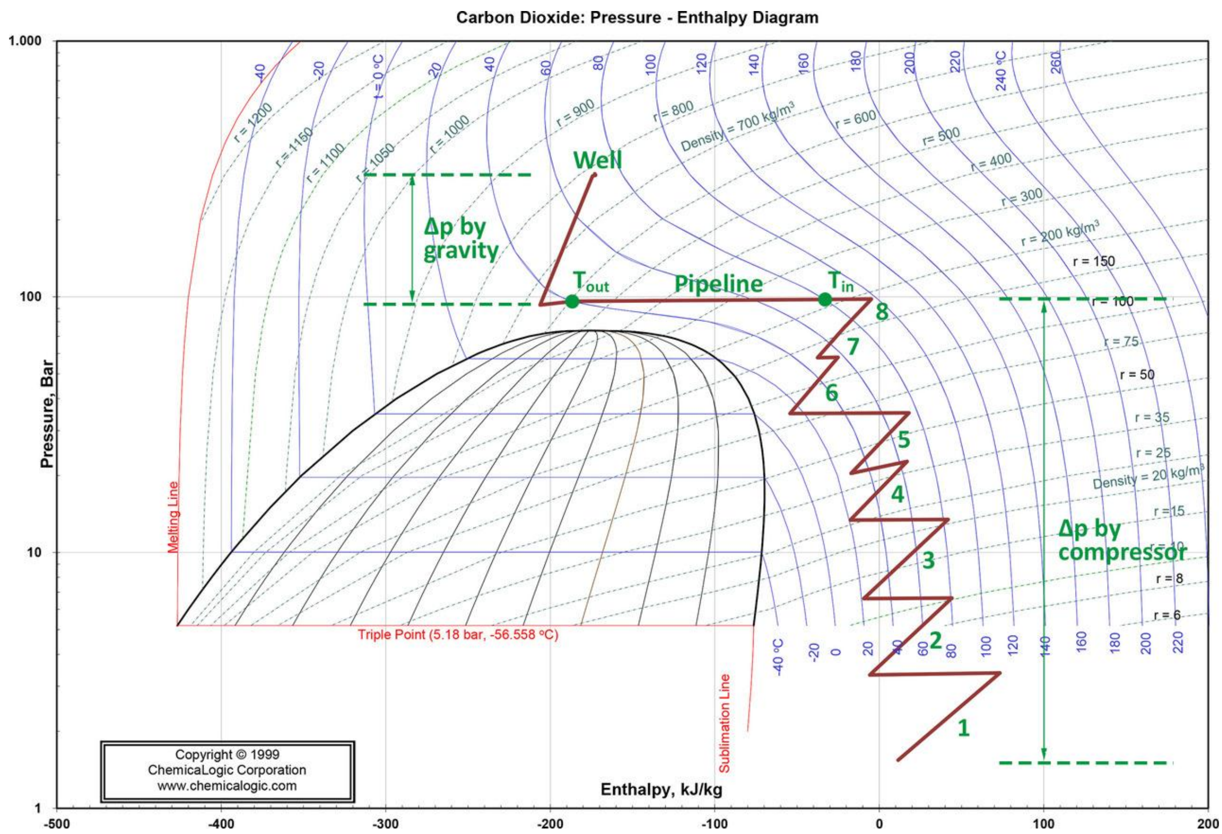
In the detailed design and engineering phase, ROAD has purchased a series of studies to confirm a firm belief in the feasibility of the total system and to obtain technical and financial data for the successful execution of the system.

3.1.1 Flow Assurance

It is important to realize that the storage of CO_2 in empty gas and/or oil reservoirs is possible due to the specific physical and themodynamic properties of CO_2. CO_2 has a critical point at 31,1°C and 73,8 bar abs. Above this pressure the CO_2 is in a dense phase, which is compressible (with an increased density at higher pressure). This creates the possibility to compress gaeous CO_2 to pressures above the critical point with commercial available compressors and let the CO_2 compress itself by the gravity head from the surface to the well bottom.

From the Figure 3.1, one can understand the overall process of the transport an storage of the CO_2 from the outlet of the capture plant to the subsea storage.

Figure 3.1: Mollier Diagram and Compressor Stages



To develop this basic idea into a practical solution for the transport and storage of CO_2 the ROAD team has performed a flow assurance study in close cooperation with TNO and was made possible by the simulations of the OLGA system software, and the theoretical and practical knowledge of the TNO staff. They have produced various reports for the transport and storage parts of the project in which their findings and recommendations are given. In addition, ROAD conducted further in-house work.

The ROAD team has composed an extensive report on the technical issues of the transport part of the project including an explanation of the results of the flow assurance work. This report was written for the Global CCS Institute.

On the site of the GCCSI one can find the report and the webinar that was organized by the Global CCS Institute.

- https://www.globalccsinstitute.com/publications/road-project-flow-assurance-and-control-philosophy
- https://www.youtube.com/watch?v=FPZxXX0fx40

The report is also also included as Ref 6 in the Annexes. For a full understanding of this topic, it is recommended to read this report.

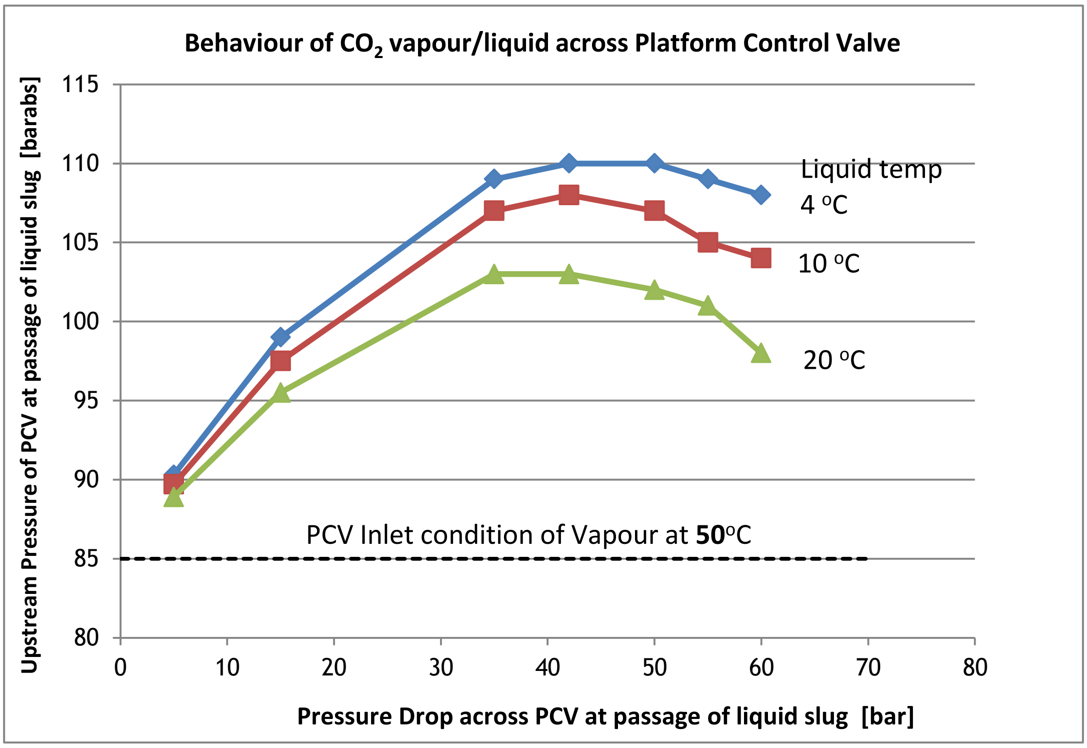
Major conclusions / recommendations are:

1. Safe and reliable operation of the proposed system is feasible and backed by simulations by the Olga program
2. The preferred pipe size is 16”
3. During initial operations the CO_2 should be transported warm to avoid blocking of the well piping and to avoid slug formation. The pipeline should be insulated to avoid heat losses. 80^{o}C at the inlet was found to be warm enough to avoid two-phase flow and keep the well bottom warm enough to prevent hydrate formation at the well bottom. The CO_2 cools to 40-50^{o}C at the well-head, and for an empty reservoir, about 10-15^{o}C at the well bottom.

The simulations of Olga indicated that at the initial phases of start-up after a plant shutdown, when the pipeline is cool, a mixed flow of liquid and vapour CO_2 may occur in the pipeline. This might give operational instabilities, vibrations, unpredictable pressure drops and consequent low temperatures after mechanical constrictions.

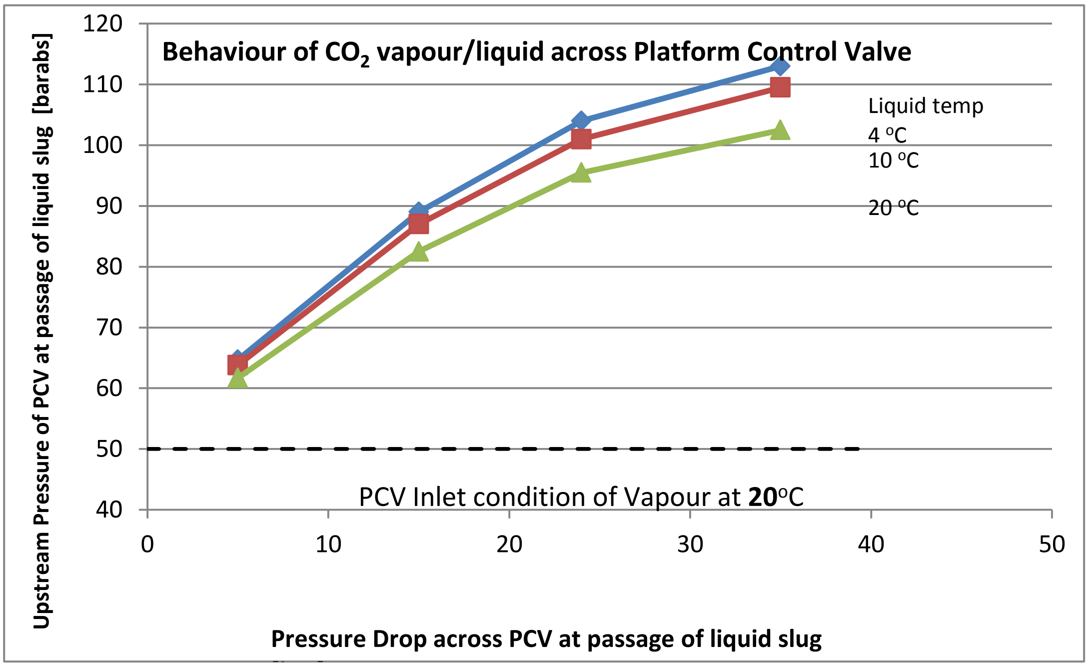
However a simple and preliminary calculation of the slug behavior suggest their moderate nature and that it is likely that the slugs do no harm to the equipment.. The occurance of slugs can further be minimised by emptying the pipeline as far as possible during shutdowns, and by using a low flow rate in the first phases of the start-up process. Details of the proposed control philosophy are given in Ref 6.

Figure 3.2: Behaviour of CO_2 vapour / liquid across a partially open Platform Control Valve



The moderate behavoiur of the slugs is illustrated by Figures 3.2 and 3.3. These show the results of preliminary calculations assuming an infinite liquid slug strikes a partially open platform control valve. The peak pressure spike varies according to the assumed conditions, but the maximum calculated across a range of conditions was 110 bar. This is well below the pipeline design pressure of 140 bar.

Figure 3.3: Behaviour of liquid slugs at Platform Control Valve



After this analysis of slugs during start-up, the ROAD team became increasingly confident that two-phase flow and consequent slugs can be managed without harmful effects. However, work on P18-4 had stopped. If the opportunity arises for further investigation, it may be possible to design the operating philosophy and equipment to tolerate two-phase flow in steady state as well as at start-up. This would make the pipeline insulation unnecessary, and allow operation of the pipeline at lower pressure, reducing the compression power requirement.

3.1.2 Route Engineering

Overall Routing of the pipeline (shown in Figure 3.8)

As the pipeline should be planned in the pipeline corridor of the Municipality of Rotterdam, ROAD has asked the Engineering Bureau of the Municipality of Rotterdam to perform a pipeline routing study to determine a safe and free pipeline location which at a later stage will be approved by the Port Authority of Rotterdam.

The Municipality of Roterdam has given ROAD a route in the pipeline corridor, running from the exit of the EON/Uniper MPP3 site following the pipeline corridor to the Yangtze Canal, a slot for the directional drilling to cross the Yangtze Canal and underpass the Euromax Terminal. The pipeline will pass well below the bottom of the Yangtze canal to avoid blockage of the shipping traffic in the harbor. After passing the Yangtze canal and Euromax terminal, the route will continue in the pipeline corridor till the point where the pipeline will exit the Maasvlakte and passes under the Maasmond, the entrance of the Rotterdam harbor with very heavy maritime traffic (Ref 7).

Routing on the EON/Uniper MPP3 site

Before the pipeline enters the corridor, it runs on the EON/Uniper site partly above ground, partly underground. The pipeline will here be equipped with flow measuring devices, temperature and pressure gauges, a pigging station and valves.

Engineering of the pipeline route in the pipeline corridor

ROAD entered into a contract with Tebodin to perform the basic and detailed engineering of the pipeline in the corridor. The main features of this engineering were:

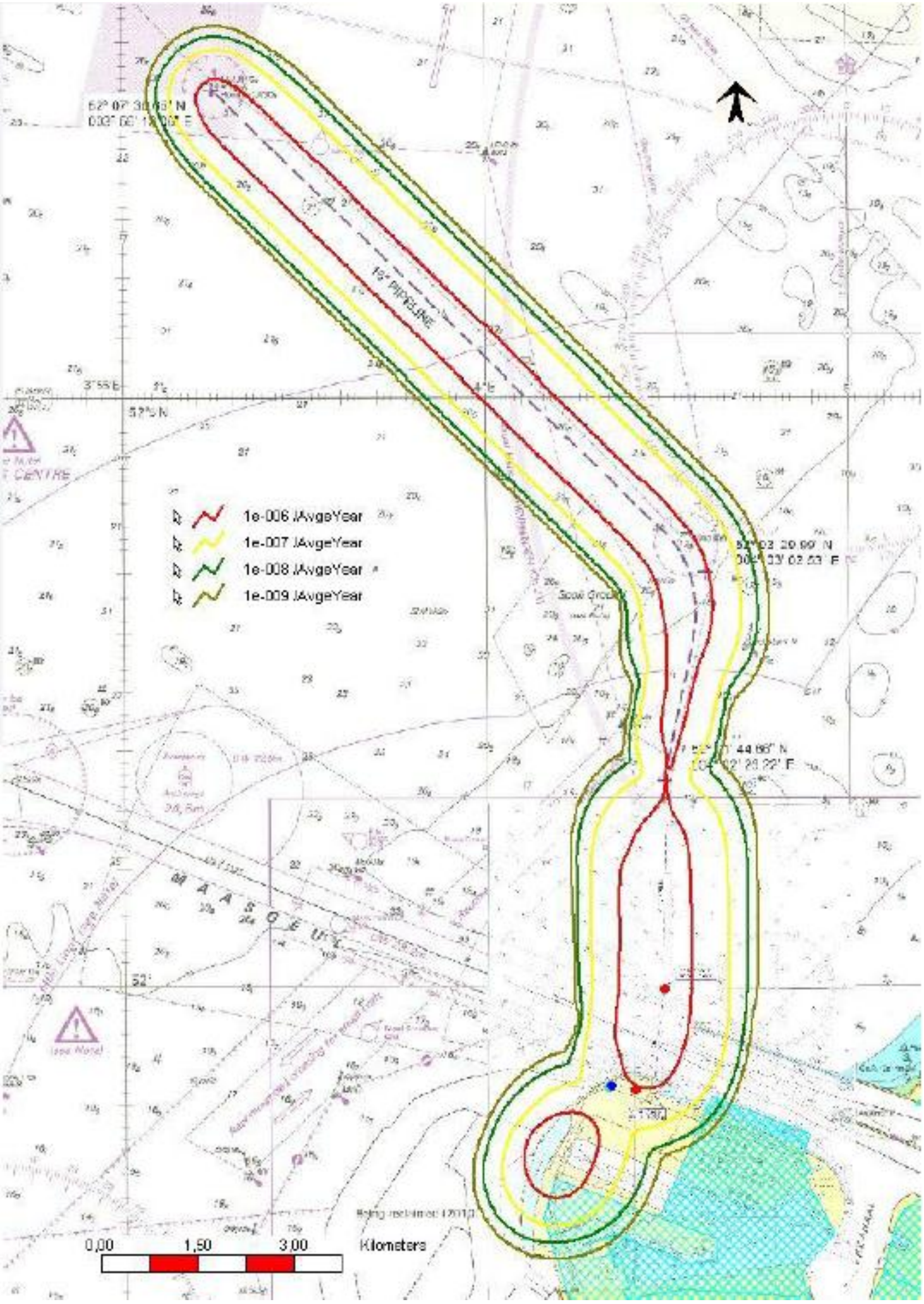
1. A large number of expansion loops to accommodate the expansion of the pipeline at high (maximum 80^{o}C) temperature.
2. Various crossings of harbor railroads and existing pipelines in the corridor.
3. A long directional drilling with expansion loops on both sides under the Yangtze Canal. This directional drilling also runs under the container storage and handling area of Euromax, and under the railroad adjacent to the container storage area.
4. According to the rules of the Dutch Railways, the pipeline has to cross the railroad at a specific depth (12 m) for safety reasons. This sets the minimum depth of the pipeline under the Euromax area. ROAD and Euromax have made an agreement to limit the possible risk to the pipeline by construction and container handling activities on the Euromax premises.
5. A long directional drilling under the Maasmond to reach the starting point of the off shore pipeline to the Taqa platform.
6. ROAD has ordered Visser & Smit Hanab (a Dutch pipeline contractor with extensive drilling experience) to prepare feasibility studies for the two directional drillings under the Yangtze Canal and the Maasmond. Drawings are attached as Ref 8 and Ref 9. Tebodin has used the results of these feasibility studies to detail the pipeline engineering.
7. Mechanical calculations:
   - Wall thickness of the pipe and pipe related items.
   - Mechanical expansion of the pipeline and the drillings.

- Two railroad crossings.
- Crossings of other pipelines and cables.
- Kathodic protection.

Safety aspects of transporting CO_2

Special attention has been given to the safety aspects of the CO_2 pipeline adjacent to the natural gas pipeline of the Gasunie. Initially a Quantitative Risk Analysis (QRA) has been made by Tebodin for the CO_2 pipeline (Ref 10).

Figure 3.4: Individual risk contours (high pressure variant)



In a later stage, the gas pipeline operator Gasunie filed a complaint that their gas pipeline adjacent to the CO_2 pipeline sees an increased risk in case of failure of the CO_2 pipeline and subsequent cooling of the gas pipe by very low temperature CO_2.

ROAD has - with the help of Tebodin - replied with the argument that the additional risk was limited due to the fact that the gas pipeline is situated only on one side of the CO_2 pipe thus only a proportion of possible failures would create an impact on the Gasunie pipeline. The Rijksinstituut voor Volksgezondheid en Milieu (RIVM), the governmental Institute that approves QRA's, however has decided that the probability of failures over the full circumferential area should be used in the calculation.

Kema prepared an updated QRA to reflect this decision (Ref 11). The risk level was was still within the expected norms, so the desgn was accepted on this basis.

Figures 3.4, 3.5 and 3.6 show the results of these calculations. Figure 3.4 shows the risk contours for the worst case (high pressure) for the off-shore pipeline section. Figure 3.5 shows the onshore pipeline risk contour just considering the risk of failure of the CO_2 pipeline itself, so without risk on consequential damage to the nearby gas pipeline. Figure 3.6 shows the updated QRA for the onshore pipeline including the worst case risk of consequential damage to the nearby gas pipeline.

Figure 3.5: Individual risk contours (failure of high pressure CO_2 pipeline without nearby pipelines)

Figure 3.6: Individual risk contours: failure of high pressure CO_2 pipeline with worst case risk of consequential failure of the nearby gas pipeline

Soil Investigations

ROAD asked the company Wiersema to perform soil investigations for the complete onshore trace and the drillings

Wiertsema gave advice on the total interaction between soil and pipe and the results were made available to Tebodin to finalize the mechanical calculations required for a safe pipeline design. The advice was made based on the investigations of Wiertsema combined with public soil data furnished by the Municipality of Rotterdam. The advice was applicable on the pipeline corridor, the crossing or the Yangtze Canal and the Maasmond. The advice on the Maasmond crossing was not completed due to the delay caused by the weather during the soil sampling and the progress of the project.

Finally a **water drainage advice** (“Bemalingsadvies“) was made to support the construction of the pipeline.

3.2 Offshore Route

Pipeline route from the Maasmond crossing to the Taqa platform

GDF/ROAD has ordered Fugro to perform a route survey for the offshore route.

Fugro has reported a route based on a detailed survey. The route runs partly parallel to the existing Taqa gas pipeline, and bends towards the platform about half way (approx. 9 km from the Maasvlakte).

The conclusions of their investigations can be summarized as follows:

- The dredged Rotterdam shipping channel will be a significant obstacle to the pipeline installation. The channel walls exhibit steep gradients, and dredging operations have produced loose, potentially unstable sediments. There is a possibility of further sediment movement and future exposure of the pipeline (if buried to a shallow depth). These factors should be considered in the pipeline design and engineering process.
- Traffic using the shipping lane will be a hazard to pipe lay operations.
- No services connecting to / departing from the P18-A platform are identified on the southwest face of the platform closest to the start of the proposed pipeline route.
- Well-developed megaripples on the route within 3km of the platform. Predominant direction of sediment movement is towards the southwest. The area to the north and east of the P18-A platform has been scoured by currents. Consideration will need to be given to sediment transportation in this area.
- Between 9.4 and 12.7 km from the platform is an area of irregular, uneven seabed with trawl scar incisions up to 0.6 m deep may have an impact on pipe lay operations, notably for a surface-laid pipeline.
- The P18-A to Q16-A 8-inch pipeline and umbilicals were not observed during the survey. Their positions should be confirmed, and considered during pipe lay operations.
- The P15-D to Maasmonding 26-inch pipeline was identified during the survey, 85 m to 110 m from the proposed route. The position of this pipeline should be considered during pipe lay operations.
- Three (3) unknown sub-bottom profiler contacts / magnetometer anomalies with corresponding positions were identified. All are classified as probable buried metallic debris. One of these is regarded as a significant target. Caution is advised at the locations of all three of these targets.
- Thirty (30) further magnetometer anomalies and eight (8) further sub-bottom profiler contacts were identified within 20 m of the proposed route. Caution is advised at the location of these targets.
- No significant debris has been identified at seabed from the side scan sonar or multibeam records.
- The seabed is extensively covered with trawl scars, indicating considerable fishing activity in the area.
- Minor sediment bedforms and small depressions have been identified along the proposed route. However, these features should not significantly affect the proposed pipe lay operations.

Pipeline spool and riser design

The design work for the pipeline spool and riser at both ends of the pipeline troute from the Maasmond crossing to the Taqa platform can be summarised as follows:

- The design and survey work of Fugro ended at the arrival at the Taqa platform.
- ZEETECH Engineering B.V. has been subcontracted by GDF/ROAD to perform the detailed design of the Offshore section of the pipeline including expansion spool and riser at platform P18-A. For information, the material take-off for the off-shore pipeline is given as Ref 12
- An expansion spool of 16 m is used. The spool will be buried during the life time; therefore no hydrodynamic loads are applied for the operational case. Stress analysis has been performed based on the

ANSYS finite element model and NEN 3650 requirements for both operation and hydrotest conditions. The results of the analysis indicate that all stresses are below allowable and meet NEN 3650 requirements.

- For offshore pipeline and the riser assembly at the Taqa Platform ZEETECH has defined the materials required for fabrication and installation of the offshore section of 16" CO2 pipeline from the HDD tie-in point to the P18-A offshore platform, including riser, riser clamps and expansion spool, coating and cathodic protection.
- ZEETECH has performed the mechanical calculations of the systems, have detailed the layout and advised the required materials of construction with specifications.

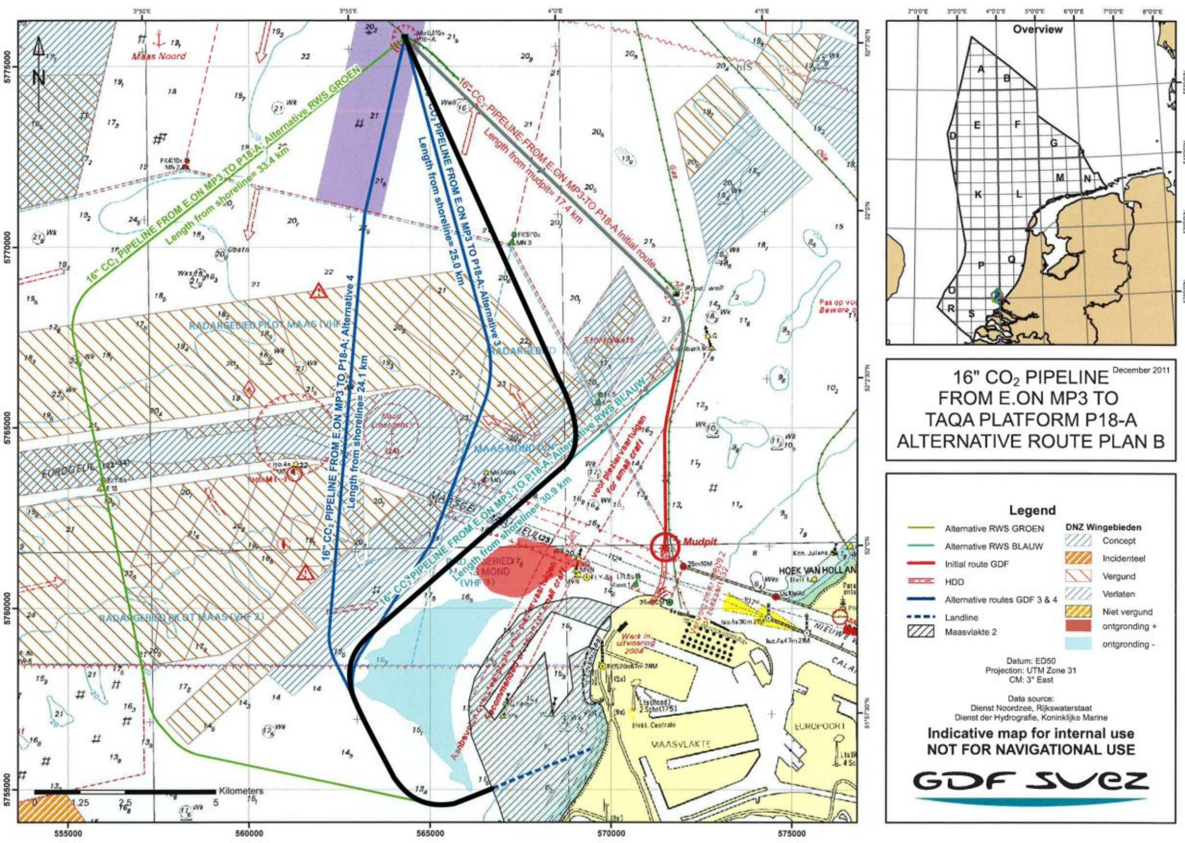
3.3 Alternative Offshore Pipeline Route(s)

From E.ON/Uniper plot to TAQA Platform

The engineering of the pipeline has confirmed that this route is feasible and will get approval of the Port and Municipality of Rotterdam. However ROAD has investigated other routes to determine the most economic. The engineered route contains two expensive directional drillings (under the Yangtze canal and under the Maasmond). The use of longer pipelines might offset these costs.

The following sketch indicates the possible routes:

Figure 3.7: Alternative Offshore Pipeline Routes to P18A Platform



The indicted pipeline routes were discussed with Rijkswaterstaat (RWS), (the Dutch governmental institute for waterways) to learn their opinion about the various routes and the feasibility of the routes.

RWS indicated that these routes crossed the area where sand and gravel are obtained. Also in these areas more ordnance could be found, making it a more unsafe route.

Further it should be realized that the routes cross a Natura2000 (protected environmental) area just before entering the second Maasvlakte.

To get a feeling for the economic impact of the routes ROAD has made a rough cost estimate comparison of two routes from the above sketch: the solid black line (Route B) and the engineered route (Route A on Figure 3.7).

This comparison gives the following data:

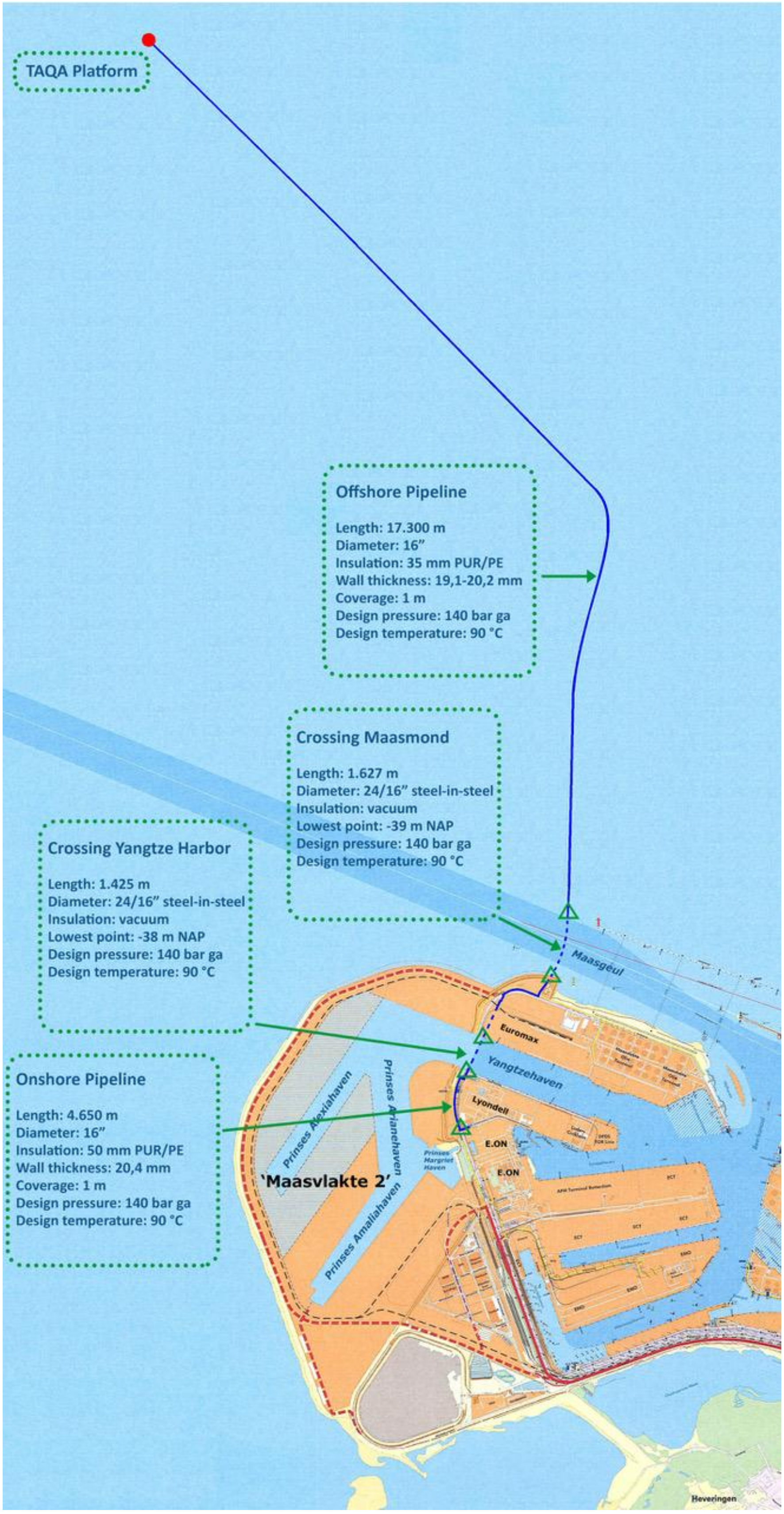
Summary of Cost Estimates of CO_2 Pipeline (40% accuracy)					
		Route B		Route A	
		length (km)	Costs	length (km)	Costs
Onshore section	Tebodin	7,42	€ 10.835.398	2,30	€ 4.294.565
HDDs MV1 or 2 to North Sea	V&SH	0,25	€ 600.000	2,90	€ 21.341.968
Offshore section	GDF-SUEZ E&P	20,50	€ 36.03.900	17,50	€ 30.110.000
			€ 47.474.398		**€ 55.746.533**

These estimates do not include:

1. the extra costs required to cross the Natura2000 area.
2. the extra costs for the longer and more complicated route on the EON/Uniper plot.
3. additional costs for safeguarding the construction in the extra dangerous ordnance area.

The ROAD management decided to stick to the original route A, for which the engineering was completed, the costs were known to a high degree of certainty and no surprises were expected. The calculated cost reduction for Route B was not deemed sufficient to compensate for the exclusions (higher and uncertain costs at the Uniper site, and for crossing the Natuur2000 area) and the fact that route B crossed identified sand and gravel extraction zones and therefore may require further significant extension to become feasible.

Figure 3.8: Engineered Pipeline Route to P18A (Route A)



4. Design and Engineering Phase (Q16-Maas)

This section describes the engineering development of the transport pipeline to Q16-Maas, developed from 2015 to 2016. Furthermore, it summarizes a study that looked at a possible connection to the existing OCAP CO_2 pipeline in Rotterdam, which supplies CO_2 to greenhouses.

4.1 Alternative Project Set-Up: Pipeline Route to Q16-Maas

Following the introduction of the slow mode in 2012, ROAD investigated options to reduce the capital costs of the project. This included an alternative storage location, Q16-Maas, in cooperation with ONE.

The basic idea is to avoid the high cost for the offshore pipeline and the expensive directional drilling under the Maasmond. To achieve this the cleaned CO_2 will be used for enhanced oil- and gas production to ONE and stored in the depleted oil- and gas reservoir Q-16 Maas.

As can be seen in Figures 4.1 and 4.2 below, the CO_2 will be compressed at the Uniper Plant with a 4-stage compressor to a pressure close to the value of the interstage pressure from the P18-4 design (about 23 bar). From there the CO_2 will be transported to the ONE site next to Euromax, where it will be compressed with another 3 or 4 stage compressor. Because of the lack of cooling water at this location, this second compressor will cooled by air coolers. The compressed CO_2 will be fed into the well.

In the event that CO_2 is produced back from the field to supply greenhouses, additional clean-up equipment would need to be added to achieve the required CO_2 specification. Connections would also be provided to feed the cleaned CO_2 to the OCAP CO_2-pipeline grid and receive CO_2 from OCAP.

Figure 4.1: Schematic layout of the connections between OCAP, ROAD and Q16-Maas.

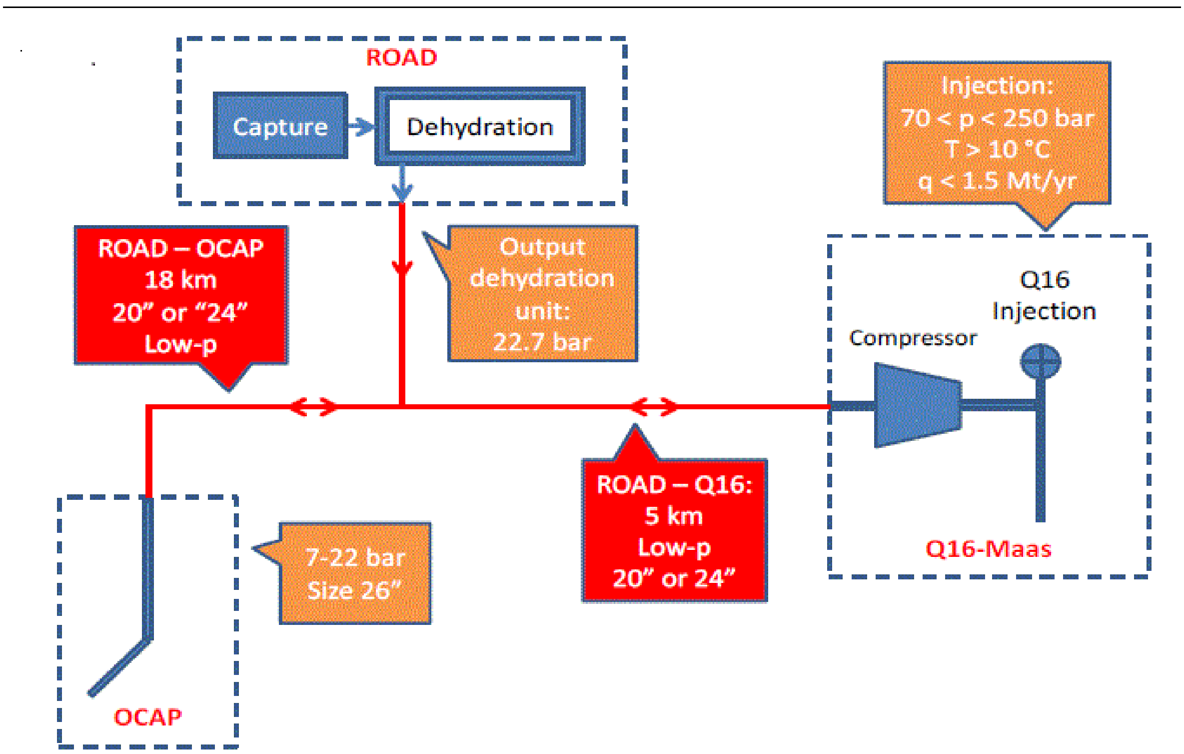
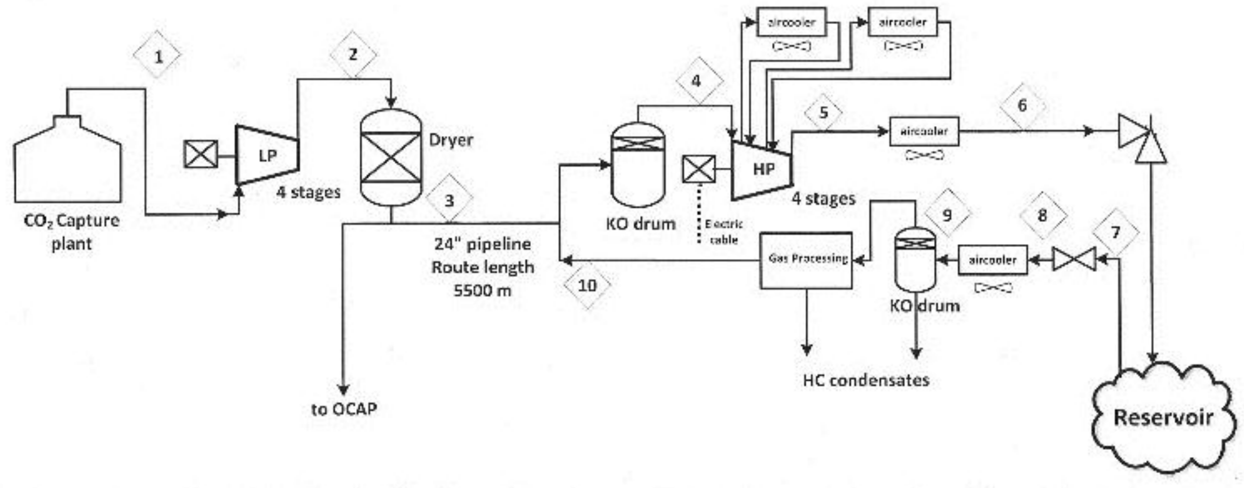


Figure 4.2: Schematic Diagram of the final proposed CO_2 transport and processing system connecting MPP3 with the Q16-Maas reservoir



4.2 Study to Connect the OCAP CO_2 Grid to the ROAD System

Both OCAP and Shell have been interested to connect their CO_2 transport system to the ROAD system to be able to store their surplus CO_2 in wintertime in the gas field and potentially for OCAP to use the stored CO_2 in summer. Shell delivers CO_2 to OCAP for use as a fertilizer in the greenhouses of South Holland.

The study investigated the use of a pipeline of appr. 18 km to connect the OCAP grid in the Botlek to the ROAD pipeline at the Uniper site.

It turned out that a 24" insulated pipeline operating at a pressure of 22 bar with a mechanical design pressure of the OCAP system of 40 bar ga, is a feasible solution.

Details are given in the published report for the GHGT-12 conference, "Update on ROAD Project and Lessons Learnt" by Read et al, and attached as Ref 13.

To accommodate the possibility to deliver CO_2 to OCAP and to receive CO_2 from OCAP/Shell, ROAD has planned and engineered scraper traps and valve stations at the exit of the EON/Uniper site.

4.3 Final Phase of the Project Set-Up

In the last phase of the project the Port Authority of Rotterdam (POR) decided to construct the pipeline themselves, and make it available to ROAD through a pipeline use contract.

This decision was made during the phase that ROAD was investigating the cooperation with ONE. The POR has re-engineered the pipeline in cooperation with Tebodin, and based it on the scope of the route scheme as given in Figures 3.7 and 3.8.

The design pressure of the pipeline was lowered to 45 bar as used by OCAP[1], and the operating temperature was lowered to ambient. As a result of these changes the expansion loops and insulation were removed from the pipeline design. This allowed the directional drilling under the Yangtze Canal to be made with conventional

[1] Although the maximum operating pressure of OCAP is currently 22 bar, this higher design pressure is used on allp pipelines to allow the possibility in future to increase the operating pressure to 40 bar.

coated steel pipe (no steel-in-steel is required for insulation). The position of the pipeline in the pipeline corridor and under the Yangtze Canal was unchanged.

During this phase ROAD learned that the Minister of Economic affairs has decided that 4 bundles of power cables for future wind farms in the North Sea will make landfall at the Maasvlakte very close to the proposed pipeline route, and extensive substation and switchyard are planned for construction in the same area. The follow-up on this item became the responsibility of the POR, but some adjustments to the pipeline route were required.

5. Annexes

The following documents are attached as Annexes to this report.

1. Process Flow Diagram Overall PFD 16” CO2 pipeline, E.ON plant to TAQA Offshore Ref 1251674_001_Rv00.
2. Piping and Instrumentation Diagram CO2 pipeline section Ref 1251663_001_Rv00
3. Piping and Instrumentation Diagram P18A Platform Modifications Connection with subsea pipeline Ref 1250699_001_Rv06
4. Piping and Instrumentation Diagram P18A Platform Modifications Connection with P18-4A well head Ref 1250700_001_Rv04
5. Piping and Instrumentation Diagram List of Symbols Ref 1251299_001_Rv01
6. Flow Assurance and Control Philosophy, Special Report for the GCCSI.
7. Report (in Dutch) for the Rotterdam Municipality, “CO_2 pipeline Maasvlakte route exploration, pipeline from E.ON power station Maasvlakte to P18A in the North Sea.
8. Drawing by Visser & Smit Hanab showing the proposed directional drilling under the Yangtze Harbour.
9. Drawing by Visser & Smit Hanab showing the proposed directional drilling under the Maasmond.
10. Report for permitting in Dutch, “QRA CO2 transport, ROAD” by Tebodin.
11. Report for permitting in Dutch, “Influence of the CO_2 pipeline on gas transport pipeline A-164-10” by Kema.
12. Report “16” CO_2 pipeline to P18-A: Material Take Off” by Zeetech.
13. GHGT-12 conference paper, “Update on the ROAD Project and Lessons Learnt” by Read, Tillem, Ros, Jonker and Hylkema, published on Science Direct in 2013.