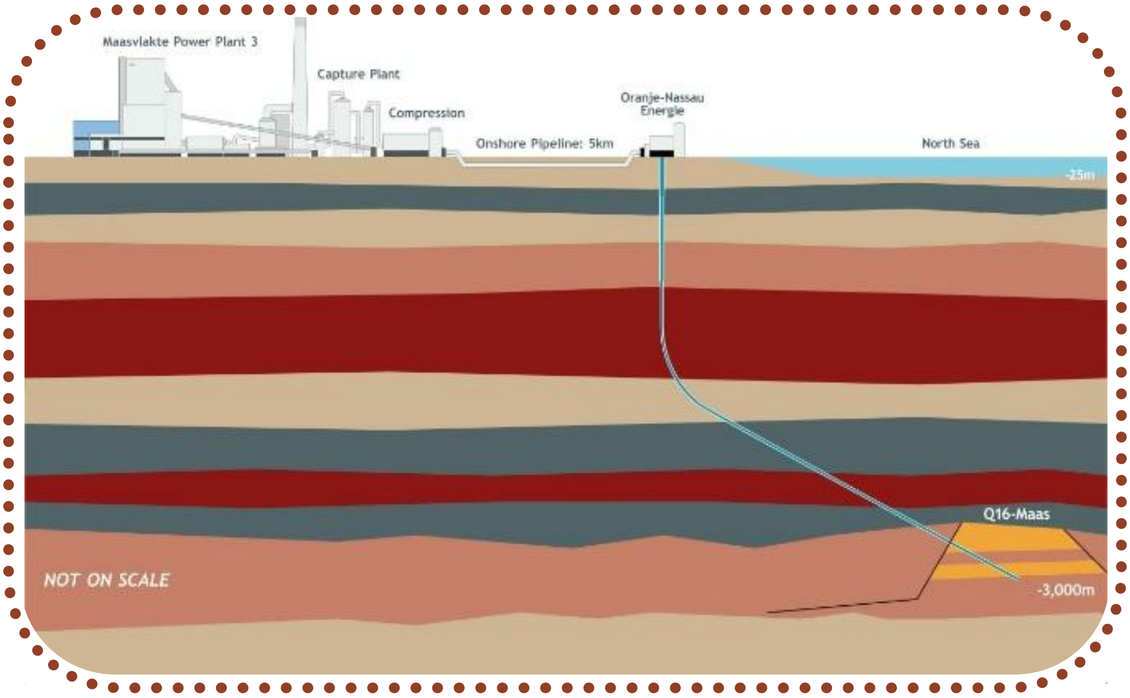
Close-Out Report Capture & Compression

Rotterdam Opslag en Afvang Demonstratieproject



Maasvlakte CCS Project C.V.

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Close-Out Report 2 of 11: Capture & Compression

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Index of ROAD Public Close-out Reports

No	Title	Scope
1	Overview	Introduce and summarise the public close-out reports.
2	***Capture and Compression***	***Technical report covering capture, compression and power plant integration.***
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.
10	Knowledge Sharing	Outline of the Knowledge Sharing & Dissemination plan as developed by the ROAD project and completed KS deliverables and actions
11	Public Engagement	Description of how ROAD organized and managed the Public Engagement process.

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1. Management Summary

Project Summary

This report summarises the technical development, design and lessons learnt on capture and compression 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 GCCSI.

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 results of the technical work on the CO_2 capture and compression system, including the connections to the power station. It focuses on reporting the design as at the end of the project (2017) as this is the most up to date, and the design as of 2012 has already been publically reported (Ref 1).

Main Highlights / Lessons Learnt

Perhaps the most important high-level conclusion from this work is that the full-scale capture plant can be designed and procured to the standard required to enable FID. All the identified technical risks, costs uncertainties and permitting and project delivery challenges for the capture plant were successfully managed. The necessary technology is considered to be available for full scale post-combustion capture.

Pilot plants have proved very valuable for testing and improving the ROAD capture plant design. Research done after the first design was fixed in 2011 led to a number of design improvements in the updated design of 2017. Most notable were the addition of a wet electrostatic precipitator to counter aerosols (which only occurs in some coal-fired and industrial flue gases), and improvement to the solvent management to minimise corrosion and solvent degradation. The solvent management package was proven on the Wilhelmshaven pilot, a joint pilot between Fluor and Uniper. The Wilhelmshaven pilot also confirmed Fluor's predictions on capture plant capture efficiency and thermodynamic performance, reducing the project risk associated with performance. We recommend that future project developers stay close to the research community to ensure state-of-the-art engineering.

A significant effort was made to optimise the integration of the capture plant with the power station, and this gave efficiency improvements, cost reductions, reduced freshwater usage and increased operational flexibility. Of particular note were:

- Use of a steam ejector enabled steam to the capture plant to be maintained at the correct pressure when the power station load (and therefore steam pressure) drops – at low capital cost.

- The overhead condenser of the capture plant was warm enough to provide an economic source of feedwater heating for the power plant.
- Condensate from the direct contact cooler can be re-used in the power plant FGD (Flue Gas Desulphurisation unit) reducing freshwater consumption.

The ROAD Project is committed to knowledge sharing, and this report contains detailed information about the capture plant and its connections to the power station. This includes information on construction and operating costs, and on health, safety and environmental issues. Also attached are references to other previously published work. It is hoped, that these prove useful to future CCS project developers.

2. Introduction

2.1 Introduction

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 "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 capture and compression system during the full duration of the project, and 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 Capture and Compression" 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 capture and compression system. This should enable readers to quickly locate information of relevance to them in this report.

2.2 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.

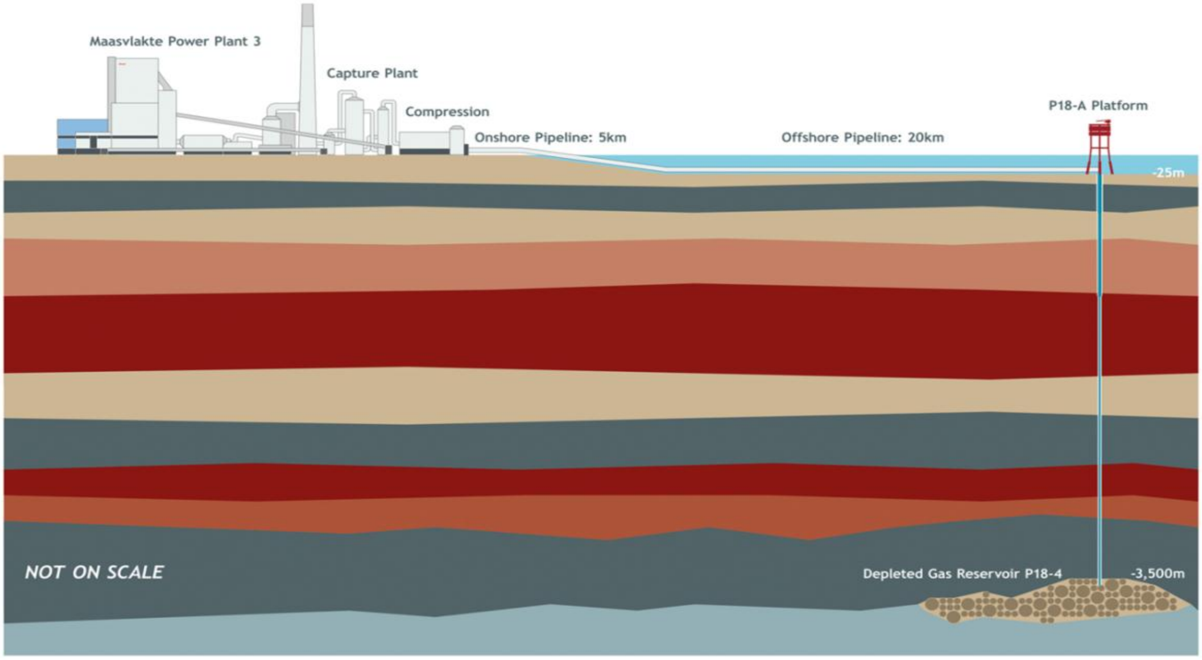
For storage in P18-4

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 2.1 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 2.1 Schematic overview of the ROAD Project using storage in P18-4



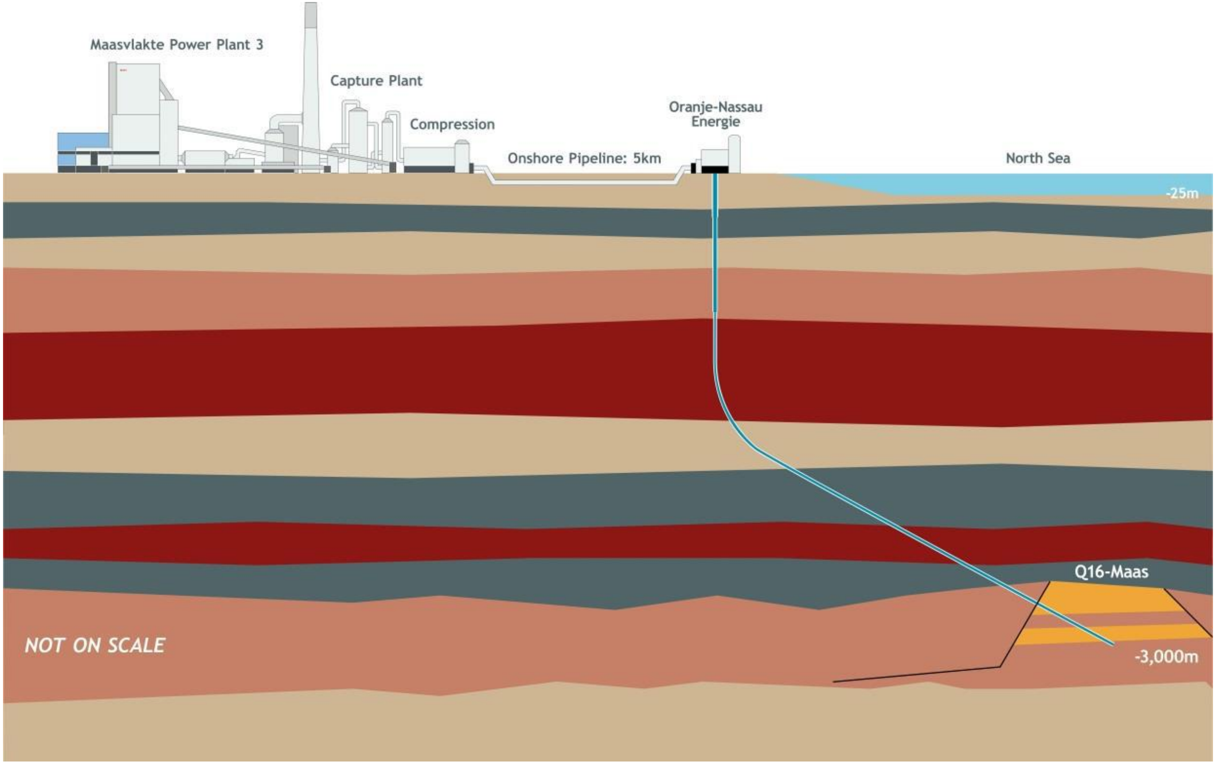
For storage in Q16-Maas

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 2.2). The selected pipeline design would have a transport capacity 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 2.2 Schematic overview of the ROAD Project using storage in Q16-Maas



2.3 Summary Description of Power Plant, Capture and Compression Process

ROAD applies post combustion technology to capture the CO_2 from the flue gases of the new supercritical 1069 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the Rotterdam port and industrial area.

The technical features of MPP3 include a pulverized-coal fired supercritical boiler with advanced materials for highest steam parameters, advanced process design and sea water direct cooling. Furthermore, MPP3 is equipped with the required emission control technologies including ‘Flue Gas Desulphurization’ (FGD) for the reduction of SOx emissions and ‘Selective Catalytic Reduction’ (SCR) for the reduction of NOx emissions. The main characteristics of the new-build power plant can be summarized as displayed in Figure 2.3.

Figure 2.3 Main design parameters of power plant MPP3

Design Parameter	Unit	Value
Rated Thermal Input	MW	2 307
Electrical Output (Net)	MW	1 069
Live Steam Pressure	bar	285
Live Steam Temperature	°C	600
Reheat Steam Pressure	bar	60
Reheat Steam Temperature	°C	620
Steam Generator Efficiency	%	94.8
Electrical Efficiency (Net)	%	46.3

The construction and commissioning of MPP3 has been completed. When operated at design conditions, MPP3 emits a flue gas stream of about 1 084 kg/s, containing 13.7% CO_2 (% volume, actual wet basis). The new-build plant therefore produces approximately 755 gram CO_2/kWh at design conditions, resulting in annual CO_2 emissions of about 5.7 million tonnes in base load operation. To lower the net specific CO_2 emissions of the plant further, Uniper is taking the opportunity to co-fire biomass.

For further reduction of the CO_2 emissions in the future, MPP3 is 'Carbon Capture Ready', i.e. it can be retrofitted with a full-scale capture plant. MPP3 has already been certified according to 'TÜV NORD Climate Change Standard TN-CC 006'. The standard contains requirements in particular regarding the technological and site-specific feasibility of retrofitting a full-size carbon capture system at the power plant location, the availability of the space which will be needed for the capture plant, the possibility of transporting CO_2 from the power plant site to a CO_2 storage site and the possible effects on plant safety and environment. The TÜV certificate was granted on 19 May 2009.

The capture unit has a capacity of 250 MWe equivalent and a target capture efficiency of 90%, which equates to 169 t/h of CO_2 captured. It aims to capture 1.1 Mt of CO_2 per year.

The capture process chosen is Fluor's Econamine FG+ process, which was selected after a thorough competitive tendering process including two competitive FEED studies (Ref 2). It is one of the best proven technologies available for post-combustion capture, and has been licensed to 28 industrial plants in a range of applications. It is based on the conventional amine solvent MEA (monoethanolamine). The layout is a fairly conventional for a post-combustion capture amine process. The flue gas is taken from the inside of MPP3 stack through a direct contact cooler (DCC) to reduce the temperature to the optimum level for CO_2 capture – typically 30-35^{o}C. The direct contact cooler also includes a small de-sulphurisation section to reduce sulphur levels in the flue gas to below 5 mg/Nm^3.

The cooled flue gases pass via a wet ESP for final particulate removal and a fan to the absorber. It is in the absorber that the solvent absorbs 90% of the CO_2 in the flue gas. The cleaned flue gas is then returned to the MPP3 stack. Solvent is regenerated in a stripper using steam from the power plant, cooled, and returned to the absorber.

In addition, the capture plant contains the following innovative features:

- The direct contact cooler (DCC) condenses water of high purity from the flue gas as it is cooled, and this is re-used in the MPP3 FGD unit. This significantly reduces the freshwater consumption of the power plant in combination with CCS (Ref 3).
- The CO_2 leaving the stripper is cooled using feedwater from MPP3 in order to recover this heat back into the power plant. This heat integration both improves efficiency and reduces the cooling water demand.
- A vacuum flash system with lean vapour compression to recover steam from the lean amine to the stripper, again reducing steam consumption, and therefore improving process efficiency.
- A proprietory low temperature and low pressure solvent management system, demonstrated at the Wilhelmshaven pilot, to maintain high levels of solvent purity and minimise corrosion, degradation and solvent losses.

The capture and compression unit also includes

- CO_2 dehydration and compression ready for onward pipeline transport to storage. For storage in P18-4, the pipeline would operate at 80-120 bar$_a$ and up to 80^{o}C, requiring an 8 stage compressor. For storage in Q16-Maas, the pipeline would be 19-22 bar$_a$ and ambient temperature (10-30^{o}C), requiring a 4 stage compressor.
- Electrical substation and control room building
- Chemicals storage area, including a solvent storage tank of sufficient capacity to hold the entire plant inventory, allowing the plant to be drained and cleaned for maintenance without loss of solvent.

The Capture Plant is designed as a demonstration of full-scale carbon capture on coal-fired power plant. Therefore, despite the cost pressures that have resulted in a minimisation of plant redundancy and spares, and the limited operational funding currently available, the Capture Plant includes all the major characteristics a full-scale commercial plant would require. These including:

- Design life of 126 000 operating hours over 20 years
- The ability to follow the load of the power plant, with the same ramp rates (up to 5%/minute)
- Turndown to 40% capture rate (This is a typical turn-down capability for a coal power plant, although MPP3 is designed to turndown as low as 25%).
- A high level of automation and instrumentation

2.4 Scope and structure of this Report

The capture and compression plant developed in 2010-2012 for application to the P18-4 storage facility has been reported publically already (Ref 1). Also publically reported were the supplier selection methodology (Ref 2), and a report on integration with the power station (Ref 4).

Following the “slow mode”, a number of scope changes were required due to updates on the power plant, and due to the change of storage location. Together, Fluor and ROAD also took the opportunity to update the capture plant design with the latest lessons learnt from pilots and other CCS projects, to ensure the capture plant remains a “state-of-the-art” design. The next section (Section 2.5) explains the scope and design changes made between 2012 and the update of the engineering design in 2017.

Section 3 gives the updated engineering design, and is intended as an update to the Non-confidential FEED study published in 2012 (Ref 1). It includes the basis of design, process descriptions, process block flow diagrams, performance data, and equipment lists.

Section 4 covers health, safety and the environment, including emissions. On this topic, there was little change from 2012 to 2017 so this is covered comparatively briefly.

Section 5 gives an update on costs, covering costs of the work done, and cost estimates for the construction and operation of the plant. These cost estimates were made by the ROAD project team, combining information from suppliers and experience from power plant and CCS pilot plant operation. The contruction programme is also included.

Although much of this report simply describes the engineering solutions reached by the engineering teams working on the project, there are nevertheless a number of lessons learnt that are more generally applicable to carbon capture plant. These are reported above in the Management Summary.

2.5 Engineering / Scope Changes between 2012 and 2017

This section describes the scope changes between 2012 and 2017, and so identifies the areas where the design described in this document differs from that reported in the non-confidential FEED study report (Ref 1)

The scope changes are summarized as follows:

- The change to the storage location results in a lower operating pressure for the CO_2 exported from the MPP3 site, and a more relaxed CO_2 specification with respect to water content. The revised CO_2 pipeline specification is given in Section 3.11.
- The possibility of CO_2 supply to greenhouses means that a tighter CO_2 specification needs to be considered as an option for future retrofit. This primarily concerns water, which must be reduced from 150 ppm_v to 40-50 ppm_v. However some solvent degradation products (ethylene and acetaldehyde) may also slightly exceed current limits, which are based on CO_2 standards for food use. Given that the CO_2 is heavily diluted before use in the greenhouses, it is very unlikely that these

impurity levels are a risk to health or crops in practice. However, the updated design should include the option to add equipment to meet the OCAP specification in future should it be necessary.

- The power plant MPP3 now has an industrial customer taking steam at 60bar and 20bar, and optional future plans to provide low-grade heat via a hot-water pipe to residential and industrial customers in the Westland area and towards Den Haag. These changes mean that at part load, and possibly in future at full-load, the LP steam supply from the power plant will fall below the 3 bar pressure required by the capture unit. The capture unit must be designed to be able to adapt to these changes. The power plant also has additional equipment for biomass and waste co-firing, which impacts on the layout of the pipelines connecting MPP3 with the capture plant. In particular, the cooling water outlet duct needs to be relocated.
- Research and development activities and pilot-scale testing of Fluor's EFG plus technology since 2012 have provided lessons learnt and led to technological improvements, which should be implemented in the capture plant design. In most cases, these design changes are proposed by Fluor.

A number of design improvements were made based on pilot experience. Most were minor refinements. The major design changes due to lessons learnt from R&D were as follows:

WESP

The inclusion of a WESP (wet electrostatic precipitator) to remove aerosols from the flue gas. Research at various capture pilot plants (see, for example, Refs 5, 6 and 7) has shown that aerosols in the flue gas entering the capture plant can give rise to high solvent emissions. This was confirmed at the Wilhelmshaven pilot when aerosols were artificially added to the flue gas. These high aerosols levels only occur at some coal-fired power plants, typically those with a wet stack (as at Maasvlakte).

Tests at MPP3 have measured SO_3 aerosol levels in the flue gas to be sufficient to cause high solvent slippage from capture units, and breach environmental limits. However, these aerosol levels are very variable, and are not present at all times. This was a matter of continuing research when the ROAD project was stopped.

At the current level of understanding, based on the worst case MPP3 measurements, and the on the available pilot data, up to 99% of the aerosols may need to be removed. However, the performance of industrial WESP designs with fine aerosols is not accurately quantified, and some pilot data suggests it may be much better than current guarantee values. Also, the acceptable level of aerosols is not accurately known for the Fluor design. Therefore a lower specification of WESP (circa 90% removal) was chosen for this design update, with provision to either include an additional WESP in future (to reach 99%), or to leave out the WESP entirely, based on the results of continuing and future research, and ongoing tests at MPP3.

Acid Wash

In 2012, the capture plant design included a provision to allow the option to install an acid wash in future on top of the absorber. This provision included civil structures, space, fan capacity etc. The acid wash was intended to remove degradation products (principally ammonia) from the flue gas should higher than predicted degradatiuon occur. Following the experience of the Wilhelmshaven pilot, ROAD became sufficiently confident that Fluor's solvent management system would prevent high levels of degradation that the provision for a future acid wash was removed from the design.

Improved Solvent Manage Package

The Fluor pilot at Wilhelmshaven had problems with solvent management, which were found to be due to iron leaching into the solvent from the coal ash, which had entered the solvent in the absorber. The iron catalysed corrosion of the steel, resulting in additional iron entering the system. During the resulting studies, iron removal systems were tested, and improved reclaimer designs were tested (although the initial reclaimer design did prove to be fit for purpose in the absence of iron contamination). As a result Fluor developed an improved proprietary solvent management package including reclaimer, filters and iron removal. This proved to be very successful on the Wilhelmshaven pilot in 2016, maintaining high solvent quality continuously over a 2000 hour test run, and would therefore be implemented in the ROAD design.

3. Capture and Compression Design

This chapter contains a description of the design process and the resulting design of the capture and compression installations. The information is based on the work that was done between the start and cancellation of the project:

- The FEED study
- The work done by Fluor in the period 2011-2012
- The updated estimate made by Fluor in 2014
- The engineering update by Fluor to include scope changes and lessons learnt, in 2017

While the information in this report is non-confidential, its contents are still of value, as they give insight into the knowledge that was developed of the process.

3.1 Introduction

This section provides a process description of the Econamine FG Plus℠ (EFG+) CO_2 capture and compression plant that was designed for the ROAD project. The purpose of the proposed EFG+ plant is to recover 90% of the total CO_2 available in a 250 MW_e-equivalent slip stream of flue gas from Maasvlakte Power Plant 3 (MPP3), a 1 069 MW_e (net electric) advanced supercritical power plant. The EFG+ Plant produces approximately 4 057 t/day of CO_2 (dry basis) that will be compressed and sent to the EFG+ plant battery limit to be transported through a pipeline to off-shore storage in the North Sea.

The Process Flow Diagrams can be consulted in the Annex (Section 6.1)

3.2 Basis of Design

As mentioned in the introduction, the overall basis of the CCS plant design is 90% CO_2 capture from a flue gas stream that is equivalent to $250MW_e$ or 23.4% of the flue gases from MPP3. Combined with the assumed electrical efficiency of the power plant, 46%, this gives 47 kg/s CO_2 for storage. For convenience this value was sometimes used in subsequent calculations when approaching the design from the capture-to-transport interface.

The base design case material balance uses the annual flue gas emission limit values for NOx and SOx. Since only long-term averages in NOx concentration affect the EFG+ process, no additional material balance was provided for the higher daily average limit value for NOx. Equipment related to SOx removal was sized to handle the higher daily average limit value of SOx in the flue gas. All other equipment sizing will be based on annual NOx and SOx average flue gas concentrations.

The plant was designed for an annual operation of 7 000 hours and a total operating life of 126 000 hours over 20 years. The equipment sparing was to be in accordance with the annual operating hours requirement. The plant was designed for a turndown to 40% of the design flue gas capacity. Sufficient chemical storage was provided in the CC-Plant for 30 days of consumption without refilling, except for nitrogen that would be for 15 days.

The following design margins were utilized in the capture plant design:

- Blower: 110% flow / 121% pressure rise
- Lean Vapor Compressor: 104% flow / 108% pressure rise
- CO_2 Product Compressor: 104% flow / 108% pressure rise
- Plate & Frame Exchangers: 20% added to required heat transfer area for fouling, in addition to vendor design margins
- Reboilers: 20% added to required heat transfer area for fouling, in addition to vendor design margins

- Balance of Shell & Tube Exchangers: vendor design margins only
- Pumps: 110% flow / 121% variable pressure rise

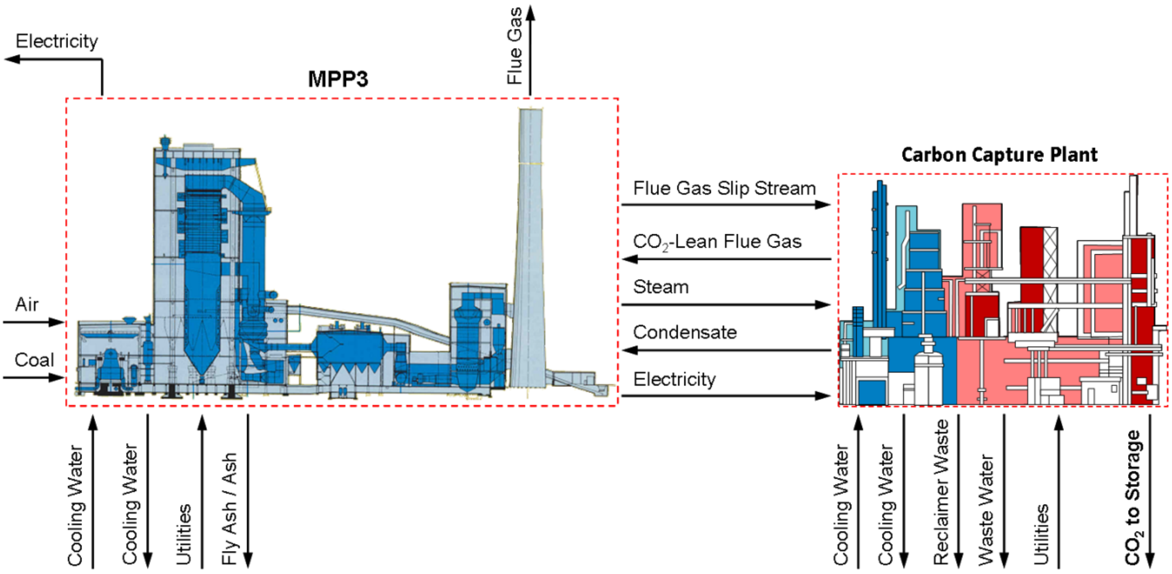
3.3 Power plant integration

3.3.1 Power Plant Integration Overview

In the period 2012 - 2013 several publications were written about the integration between the CCS installation and the power plant. In 2012 a presentation was given at the POWER-GEN conference (Ref 8) and in 2013 a special report was written for the GCCSI (Ref 4). Some highlights from these documents are summarized below, together with a discussion of the changes since 2012. For the complete data we refer to the original documents.

There is a range of interactions between the capture plant and the host power plant, MPP3, as illustrated schematically in Figure 3.1 below.

Figure 3.1 Illustration of the interfaces between the power plant and the CCS installation, and with the outside world

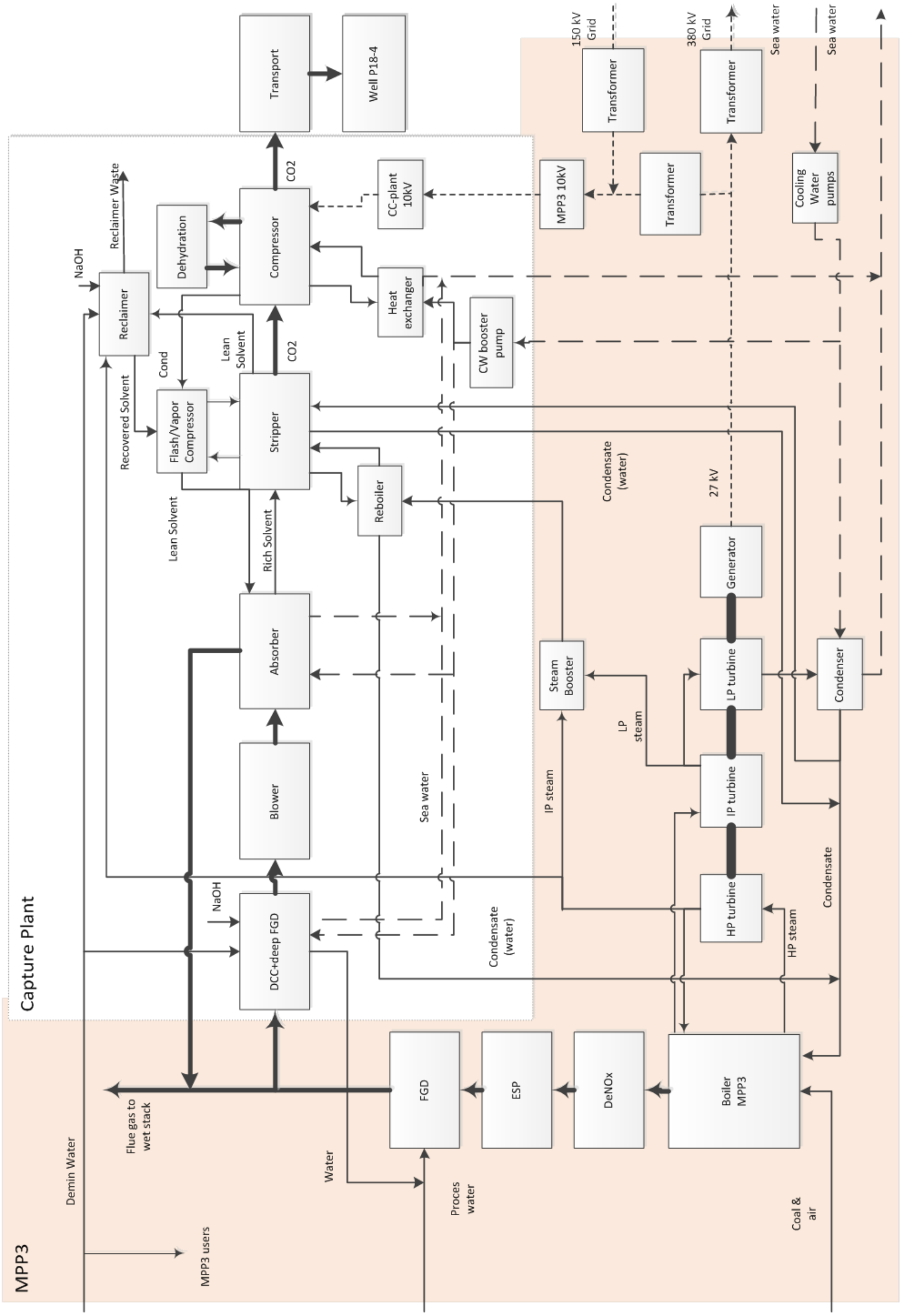


The integration of the power plant, capture, transport and storage was and still is novel to the EU. One existing reference is the Boundary Dam project in Canada which is smaller (roughly 140 MW scale) and uses different capture and storage technologies (Boundary Dam storage is in an onshore EOR field with test-scale aquifer injection in addition, whereas ROAD uses an offshore depleted gas field). The integration of the capture plant with the power plant, compression, pipeline and depleted gas field storage is therefore a first-of-a-kind. The ROAD design includes no intermediate storage (other than that provided by pipeline line pack) so the whole CCS chain will operate as a single integrated system. In addition, the capture plant process was subject to on-going continuous improvement by Fluor, supported by pilot studies involving the parent companies of the project sponsor. The plant design would therefore have included a number of optimizations and improvements not seen in existing small-scale units. These include:

- Heat integration whereby the warm CO_2 at the stripper outlet is used to provide feed water heating for the power plant.
- A steam ejector, used to control the pressure of the steam from the power plant, allowing continued efficient operation of the capture plant when the power plant is at part load.
- Vacuum flash and compression system on the reboiler and intermediate absorber cooling in the solvent cycle to optimize the process performance (minimizing the energy required).

- Use of the latest packing designs and washing / scrubbing designs for optimum thermal and environmental performance.

Figure 3.2 Block diagram integrated chain (MMP3, capture plant, transport and storage)



In the block diagram (Figure 3.2) the main installations, transport and storage blocks are shown, as well as the integration of the capture plant with MPP3:

- flue gas extraction from the main flue gas duct;
- return of treated flue gas from capture plant to main power plant stack;
- low pressure (LP) steam extraction from steam turbine to capture plant's reboiler;
- return of steam condensate from capture plant's reboiler into steam cycle;
- cooling water for capture plant's coolers from main cooling system inlet;
- 'cold' condensate from pre-heater train to capture plant coolers for waste heat recovery;
- heated condensate return to pre-heaters train;
- electric power supply to capture plants via power plant's auxiliary system;
- utilities (e.g. de-mineralized water).

Between the moment that the project went into slow-mode, and the restart at the end of 2016, the boundary conditions for the capture plant, as well as for the host power plant, changed significantly. In 2013, the decision was taken to close the neighbouring power station units MPP1 and MPP2, which supply steam to neighbouring industry. This steam supply was transferred to MPP3, affecting the available steam pressure the capture plant can use. After extensive modelling it was concluded that the proposed LP steam connection can still be used, at least when the power station is at or close to full-load, which currently is most of the time. However, the cold reheat connections which were used to supply steam for the steam ejector cannot be used. The steam ejector must use hot reheat steam instead, which is more expensive. Thus when MPP3 is at part-load, the steam for the capture plant reduces the MPP3 output more significantly.

Also, some of the proposed pipeline routes for the interfaces had to be redesigned, as new equipment like silos for biomass co-firing, were now blocking the route of the original design. The updated pipeline routes are shown on the plan of on-site pipeline routes, Annex 6.4.

In the following sections, each tie-in is summarized

3.3.2 Flue gas tie-ins

MPP3 has a wet stack with no gas-gas heater. This means that the flue gas extraction and return can be anywhere after the FGD (normally must be between the FGD and gas-gas heater). Three positions were evaluated to extract the flue gas from MPP3 to the capture plant:

1. On top of the FGD of MPP3
2. In the horizontal Glass Reinforced Plastic (GRP) duct from the FGD to the stack of MPP3
3. Inside the stack of MPP3 where the GRP duct turns upwards.

The position inside the stack was chosen to avoid changes to the original plot plan of MPP3 and to minimize supporting structures and scaffolding for the ducting from the tie-in points to the capture plant. The stack can be used to support the new tie-in structures and an obstacle free routing downwards is available inside the concrete stack.

The discharge of the treated flue gas, which has a volume flow of approximately 566 000 Nm^3/hr at 35°C will be routed back to the wet stack of MPP3.

The parameters for the flue gas are given in Table 3.1

The flue gas tie-ins have been installed in the stack of MPP3. Although the intake and the return ducts are physically close to each other, computational fluid dynamics modelling showed that there would be negligible recirculation of flue gas from the outlet to the inlet, even with the power plant at very low loads. Figure 3.3

shows a cross-section of the stack showing the location of the tie-ins and photographs of the tie-ins during and after installation.

Table 3.1 Flue gas parameters

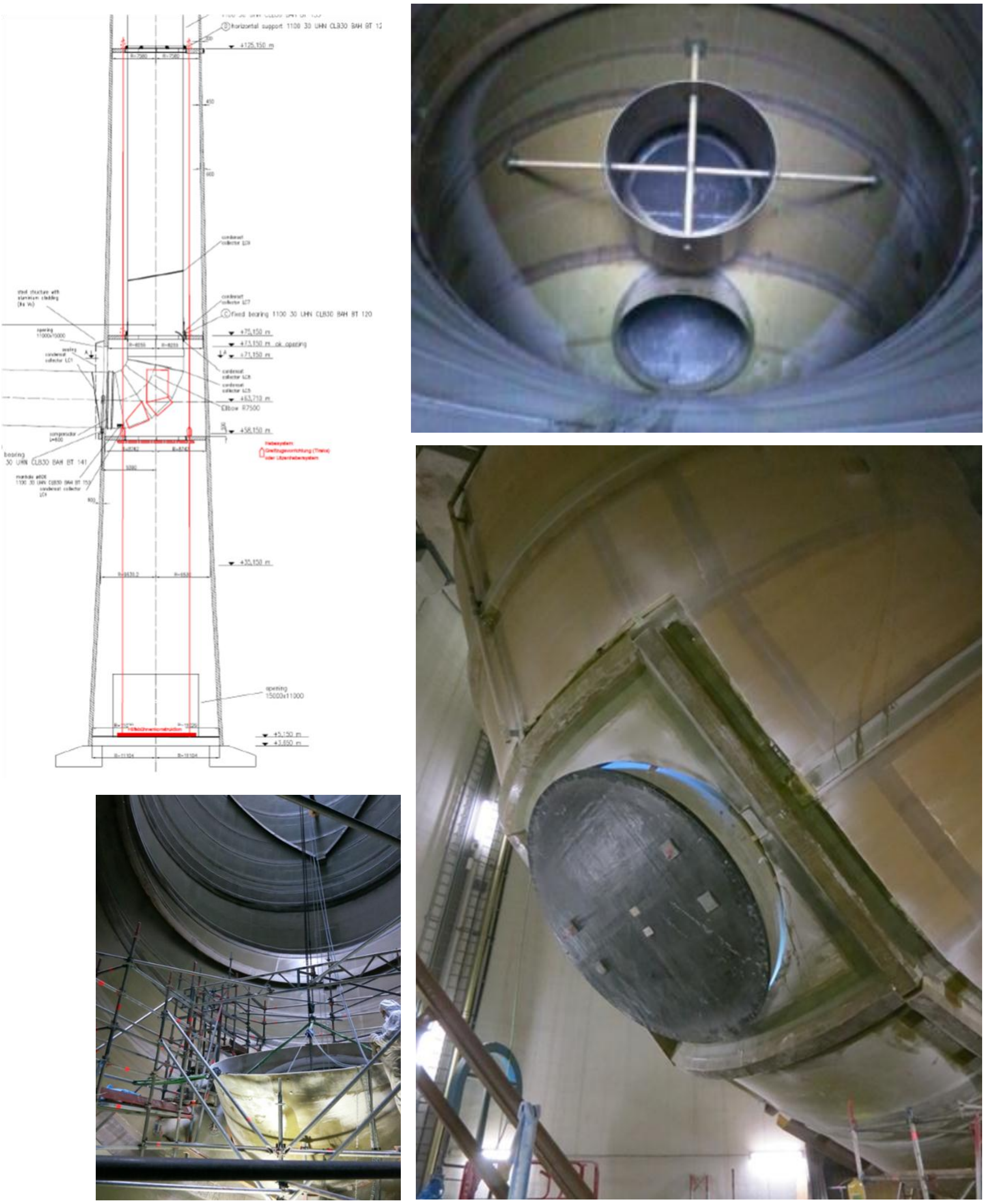
Parameter	Unit	Value
Flue Gas Volume Flow (STP, wet) from MPP3 (after FGD)	m^3/hr	3 006 580
Flue gas flow to capture plant (STP, wet)	m^3/hr	700 000
Flue Gas Temperature to Capture Plant	^oC	48.2
Flue gas pressure (guage)	Mbar	+ 2.0
Composition to Capture plant		
• **H_2O**	% vol	11.2
• **CO_2**	% vol	13.7
• **N_2**	% vol	70.9
• **O_2**	% vol	3.4
Flue gas flow return from Capture Plant	m^3/hr	567 000
Flue Gas temperature return from Capture Plant	^oC	34.9
Composition to Capture plant		
• **H_2O**	% vol	5.7
• **CO_2**	% vol	1.7
• **N_2**	% vol	87.4
• **O_2**	% vol	4.2

3.3.3 Steam Supply

The capture plant requires a substantial amount (>100MW$_{th}$) of low grade heat (between 120-140^{o}C) for the reboilers in order to regenerate the amine in the stripper. In the early statges of the project, a wide range of sources for this low grade heat were considered including: use of an auxiliary gas-fired boiler; use of a small CHP unit using exhaust heat from a gas turbine; using existing auxiliary steam supplies, and using low pressure steam extracted from the MPP3 turbine. Because the IP/LP cross-over at MPP3 is a suitable pressure when MPP3 is at high loads, large quantities of suitable low pressure steam can be extracted from this location. This proved to be the most efficient solution, and also the lowest cost because the use of more expensive gas fuel was avoided.

However, the MPP3 turbine drops pressure as the MPP3 load is reduced. Therefore, at lower loads the steam has insufficient pressure to provide the reboiler with heat at the required temperature. Therefore ROAD also needed a practical solution for the periods when MPP3 is at low load. Options considered were:

Figure 3.3 The installed flue gas tie-in



1. Modification of the crossover pipe IP to LP turbine to install throttle valves to keep enough pressure during part load.
2. Extraction from a higher pressure source – which would have to be from the reheater due to limitations on the steam extraction capacity of the IP turbine (leading to low part load efficiency of MPP3).
3. Installing a steam jet booster (steam ejector) to increase the pressure of the steam extracted from the main extraction point using a smaller amount of higher pressure steam (more complex and extra investments).

Option 1 was initially investigated with the manufacturer of the steam turbine of MPP3 but abandoned because of the high investments, operational risks and long outage of MPP3 for the modification.

For option 2 the only suitable extraction point is the cold reheat. However, in some part load situations of MPP3 the amount of steam that can be extracted is not high enough and would require part load of the capture plant as well. Also the electrical losses are high because of the high quality steam that is used. Furthermore, the disadvantage of this option is the shifting of the steam extraction to the cold reheat during operation that is rather challenging

Option 3 was found the most economical. The high pressure steam for the steam jet booster will be extracted from the cold reheat steam pipes of MPP3. A view of the integrated process flows for the steam and condensate of MPP3 and the capture plant (brown dashed box) is shown in Figure 3.4 below.

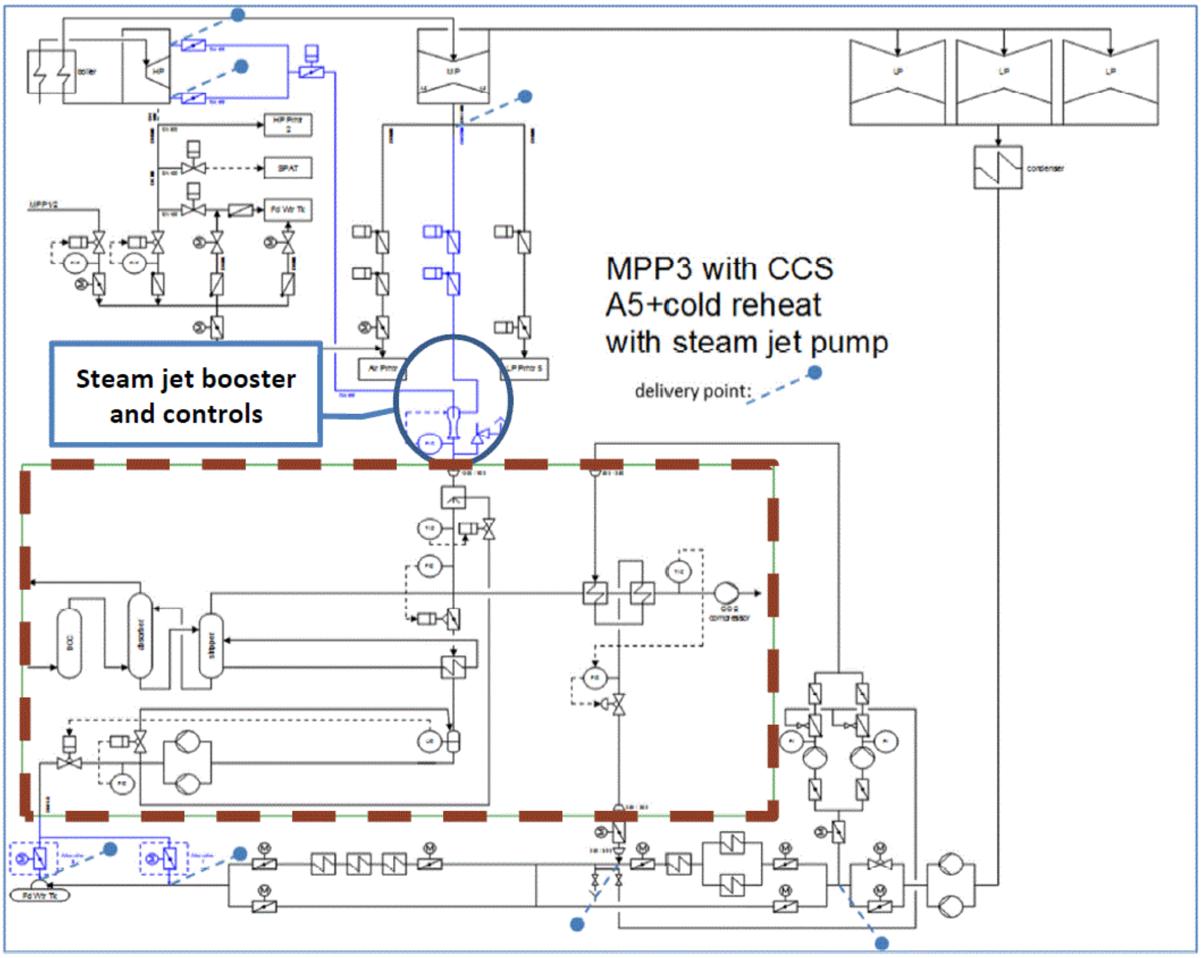
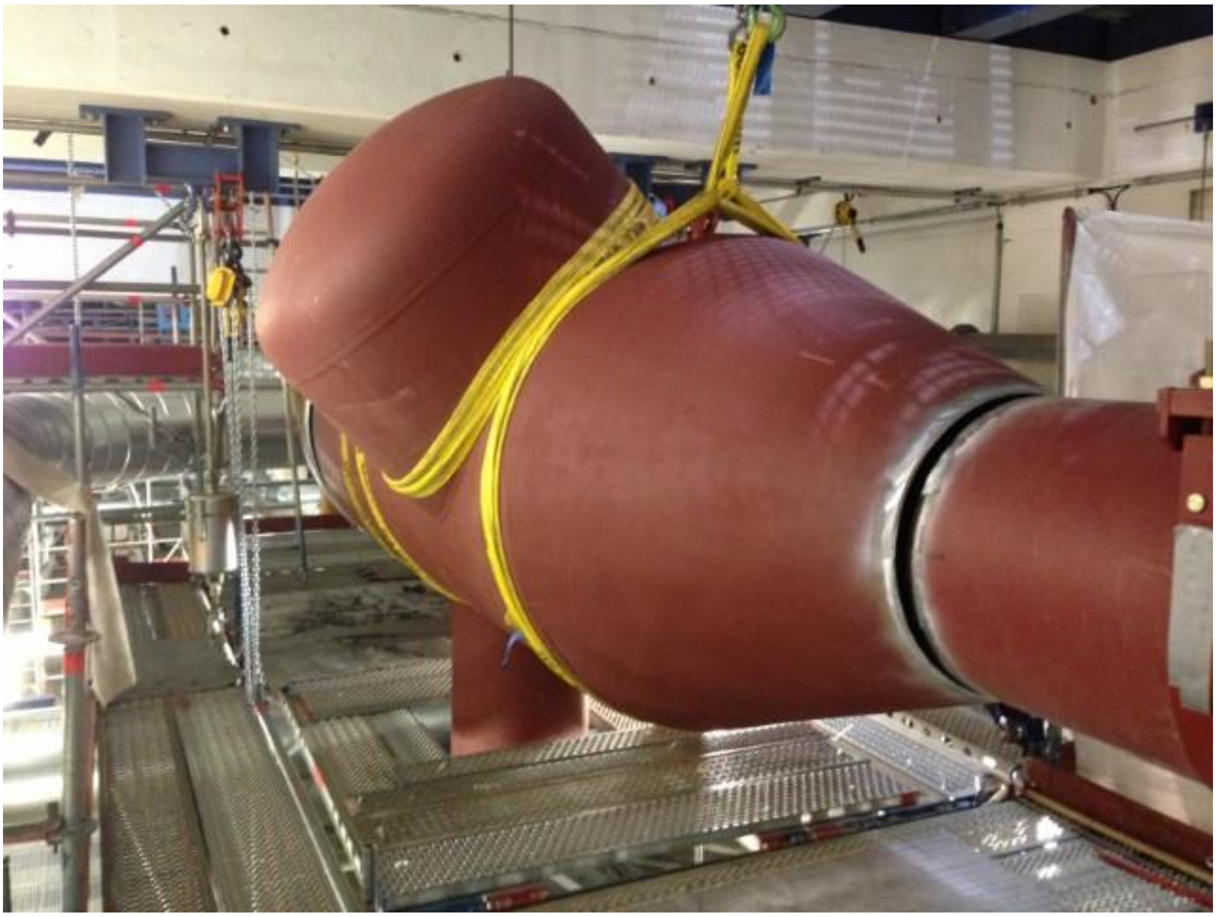


Figure 3.4 PFD of steam and condensate integration

As with the flue gas tie-ins, the steam tie-ins were installed during the contruction of MPP3 in order to avoid the need for a long outage to connect the capture plant. The installation was completed in 2013. Figure 3.5 shows the main low pressure steam tie-in durng installation.

Figure 3.5 View of the the low pressure tie-in piece being mounted (April 2013)



The tie-ins in the cold reheat were also installed at the beginning of 2013.

Unfortunately, with the addition of steam connections to neighbouring industry, by 2016 MPP3 was unable to supply cold reheat steam at part load to the capture plant. The neighbouring industry included a main steam connection which is used at low loads, resulting in lower steam flow through the reheater. If the ROAD plant uses cold reheat steam (as planned in 2010-2013), then the steam flow through the boiler reheater would fall too low and place it at risk of overheating. Therefore the 2017 design envisaged an off-take off the hot reheat (so downstream of the boiler). This is less efficient from a thermodynamic point of view, but could also be achieved at relatively low cost. It is worth noting that MPP3 only operates at part-load for limited periods, so the economic penalty of this reduced efficiency is limited.

3.3.4 Condensate for Cooling (Heat integration with the Power Plant)

Waste heat from the capture plant can be integrated in the condensate preheating train, aiming at increasing overall plant efficiency. The capture plant includes several coolers where waste heat is released to cooling water, thus dissipated into the environment. Condensate from the power plant (feed water from the main condenser) at low temperature can be used instead of cooling water, recovering heat into the main power plant cycle.

In the capture plant the following heat exchangers are potential sources for waste heat integration:

- direct contact cooler: it cools the water stream used to quench the inlet flue gas upstream the absorber;
- lean solvent cooler: cools the lean solvent before entering the absorption column;
- washer coolers: cool the solvent/water streams of the washing loops at the top of the absorber;
- overhead CO_2 condenser (OCC): cools the wet CO_2 before compression at the top of the stripper;
- CO_2 compressor intercoolers: cool the CO_2 between sequential compression stages.

After analysis of these options, only the OCC proved to be cost effective for heat integration. On the CO_2 side of the OCC the inlet and outlet temperature are 89°C and 40°C, respectively. This means that the full heat load of the condenser (28.8 MWth) can be used for condensate pre-heating. The condensate will be supplied at 19 bar(a) and 26°C as it exits from the main steam condenser; it will be returned at 16-18 bar(a) and a temperature in the range of 70-80°C and added to the main stream of condensate after the 3rd preheater, where the temperature is approximately 90°C. With respect to overall plant efficiency with capture, the integration gives an increase in efficiency of approximately 0.2% points.

This waste heat integration is chosen because the higher revenues associated with the increased power output largely compensate the higher investment cost required. Another important reason that influenced this decision is the reduction of the cooling water requirement for the capture plant. In fact, by integrating the OCC, no more cooling water is required for that cooler with significant savings in the total cooling water flow for the capture plant. It is estimated that 3 000 m^3/h less cooling water will be used, accounting for about 20% of total capture plant cooling water. Therefore, the extra investment required in the waste heat integration is not only compensated by higher revenues but also by the reduced investment for the capture plant's cooling water system.

3.3.5 Electrical Power

A 10kV connection with the MPP3 plant is foreseen to supply electrical power to the capture plant, which will need at most (peak demand) about 30MW. About half of this supply is needed for the CO_2 compressor.

Currently, the auxiliary 10 kV system of MPP3 is energized through the auxiliary transformers powered by the generator of MPP3 or the 380 kV step-up connection. In emergency situations the 10 kV system of MPP3 can also be supplied from a 150 kV grid connection to the local distribution grid operated by Stedin. Individually, these connections are not sufficient to supply both the MPP3 auxiliary load and the capture plant load. Therefore the intention is to reconfigure this system so that the connection to the 150kV distribution grid can be used to supply the capture plant while the generator of MPP3 supplies the MPP3 auxiliary load.

Therefore, the electrical power for the capture plant will be provided via a 10 kV switchgear that will be installed at the control building of the MPP3 power plant and which is linked to the 150/10 kV transformer that is connected to the external 150 kV grid. Since the supply to the MPP3 10kV system from the external 150 kV grid is required only in emergency cases (e.g. operating failures of auxiliary power transformers), the capture plant can be supplied with electrical energy via the external grid transformer.

This solution gives the lowest capex because no extra transformer or high voltage grid connection is needed and the expected availability of electrical supply for the capture plant is high enough. Disadvantages are the extra grid costs because electrical power cannot be supplied directly from MPP3. However, considering the limited number of operating hours of the CCS demo, this additional opex is outweighed by the lower capital cost.

3.3.6 Cooling Water

MPP3 uses sea water for cooling. The cooling water is pumped out of the harbour and runs under the capture plant through a channel to the MPP3 unit. The heated cooling water is discharged via a cooling water pond on the other side of the power plant into another part of the harbour.

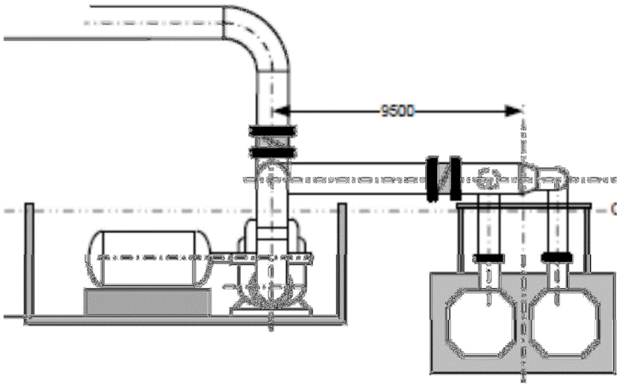
The cooling water channel crossing the capture plot is a rectangular concrete structure, consisting of two parallel square channels lying side by side, with a size of 2.55 m by 2.55 m. The channels are accessible for cleaning and inspection purposes. For this reason access hatches (manholes) are placed in the channels at regular intervals.

To supply up to 13 000 m³/h cooling (sea)water to the capture plant, it is foreseen to connect suction lines of the capture plant booster pump to two manholes (ID 800 mm) of an inspection well in the concrete cooling water channel between the main cooling water pumps and the machine house of MPP3. The two manhole covers will be replaced with (flanged GRP) DN800 pipe spools running to a suction header, which feeds the capture plant cooling water booster pump. The DN800 spool pieces will be designed in such a way that they are removable, which will allow access to the manholes when this is needed.

The concrete superstructure can be modified without operational consequences. The piping from the manholes to the capture plant can also be installed while MPP3 is in operation, which leaves only the final connection to the manholes to be done during the required stop of MPP3 for all final connections. A cross-cut of the proposed arrangement is shown as Figure 3.6

The cooling water from the capture plant will be discharged to the outlet pond through a new DN 1200 GRP pipe. The routing of this pipeline had to be changed in 2016-2017 to avoid new silos for biomass co-firing being installed at MPP3. This new route is shown on the pipeline route plan in Annex 6.4.

Figure 3.6 Cross-cut of the cooling water supply channel and connection to the booster pump.



3.3.7 Controls

The control of the capture plant is designed to be completely integrated with the control system of MPP3. The control system ABB 800xA is used by the power plant, and allows the assignment of different control functions to a local control room or to the main control room of the power plant. Therefore this control system was also selected for the capture plant, as this gives complete flexibility over whether the capture plant and the interfaces of the plant with the power plant will be controlled from the main control room or if the control of different parts of the capture plant is assigned to the local control room. In any case, in each control room it will be possible to access and/or visualize all process data.

The integration will be done by using a redundant optical fibre cable between the main control system of the MPP3 power plant and the local control system in the capture plant.

3.3.8 Various water streams

Connections between the power plant and the capture plant are also required for a set of smaller water and waste-water streams. For completeness, they are briefly described here:

- Demineralised water – to be supplied from the station’s EVIDES connection via a 250m long DN 80 pipeline.

- DCC condensate – the direct contact cooler condenses about 44 t/h of water from the flue gas. Since this is contains only impurities present in the flue gas, it can be used instead of fresh water in the power plant flue gas desulphurization (FGD) unit. This arrangement reduces the freshwater use of the power plant.
- Blowdown from the capture plant desulphurization unit. This unit uses sodium hydroxide to scrub SO_2 from the flue gas, giving a small waste water stream (average 0.3t/h) of sodium and sulphate salts. Since these are common salts naturally occurring in seawater, and since the waste stream is small, this can be discharged into the cooling water and so into the sea as part of the capture plant environmental permit.
- Reclaimer effluent – this is treated as a hazardous waste and removed for incineration off site.
- Storm water drains are monitored for contamination and (if satisfactory) sent to the MPP3 storm water drain system
- Sewage (from the control room facilities) is drained into the station sewage system
- Condensate from the MPP3 stack. Because MPP3 operates with a wet stack, a small amount of condensate collects on the stack walls and is drained at the bottom of the stack. This is currently used in the FGD. However, once the capture plant is operating, this might be contaminated with amines which would make it unsuitable for the FGD. This is estimated to be only about 0.1 kg/hour. The use for this water is not yet determined.

3.4 Process description including CO_2 compression

The Process Flow Diagrams of this section can be found in the Annex, Section 6.1. These process flow diagrams include the KKS component numbering given in the descriptions below. A simplified block diagram is given in Figure 3.7 in Section 3.5..

3.4.1 Flue gas cooling and trim SOx removal

The flue gas feed to the EFG+ plant comes from the Flue Gas Desulfurization (FGD) unit of MPP3. Flue gas from the FGD unit is first routed to the Direct Contact Cooler (DCC) (3 0HKB10 BB001) for both cooling and trim SOx removal (polishing). The flue gas cooling is done in the quench section of the DCC by circulating water. Circulating water is drawn from the bottom of the DCC to the DCC Water Cooler (30HKB30 AC001) by DCC Circulation Pump (3 0HKB20 AP001/2) and returned to the top of the column’s quench section. The circulating water is heated by the cooling and condensing of water vapor in the flue gas.

Excess water produced in the DCC from the condensing of water vapor in the flue gas is neutralized using 20 wt% NaOH. The neutralized excess water stream is held temporarily in the DCC Water Neutralization Tank (3 0HKB50 BB001) and sent to the plant battery limit using the DCC Excess Water Pump (3 0HKB60 AP001). This water is reused in MPP3 as FGD make-up water. Cooled flue gas from the quench section of the DCC contacts a circulating scrubbing solution. The scrubbing solution is circulated to the top of the column by DCC Scrubbing Solution Pump (3 0HKE70 AP001/2). A 20 wt% sodium hydroxide (NaOH) solution supplied by the DCC NaOH Injection Pump (3 0HKE60 AP001/2), along with a slip stream of cooled DCC water taken downstream of the DCC Water Cooler, are fed to the suction of the DCC Scrubbing Solution Pump. A blowdown slip stream is taken from the circulating scrubbing solution loop which is discharged to the sea as it practically only contains sodium sulfate. The cooled, desulfurized flue gas passes through a mesh mist eliminator and exits the top of the column where it is routed to the Blower (3 0HKC10 AN001) via the WESP. The 20 wt% sodium hydroxide solution is made by diluting a 50 wt% NaOH stock solution, stored in the 50 wt% NaOH Storage Tank (3 0HKE20 BB001), using demineralized water.

3.4.2 WESP, Flue gas blower and CO_2 absorption

The WESP (Wet ElectroStatic Precipitator) removes more than 90% of the remaining particulates in the flue gas, and is intended to prevent aerosols in the MPP3 flue gas from reaching the absorber, as discussed in Section

2.5. It was located after the DCC for two reasons: this is the coolest part of the flue gas flow chain and therefore has the lowest volume flow, allowing the WESP to be smaller, and also because there is a risk that the WESP converts a percentage of SO_2 to SO_3, which would itself create aerosols. The DCC removes SO_2 down to very low levels, so this risk is avoided by placing the WESP downstream of this polisher. The decision to locate the WESP before the blower was based on optimization of the flow path – for the ROAD layout duct distances are minimized by using a downflowing WESP upstream of the Blower. Space is available for a second WESP in case removal of aerosols to 99% is required. During the design update, quotes from a number of WESP vendors were received. However, the final choice of vendor was not made. The plan area allocated is sufficient for all vendor designs received.

The Blower (3 0HKC10 AN001), located downstream of the WESP, is used to overcome the pressure drop through the EFG+ plant. From the Blower, the flue gas enters the bottom of the Absorber (3 0HKD10 BB001) and flows upward through the packed column beds, where it reacts with the EFG+ lean solvent. A total draw of semi-rich solution is extracted from the column and sent by the Absorber Intercooler Pump (3 0HKD20 AP001/2) through the Absorber Intercooler (3 0HKD30 AC001-3) where the solution is cooled before being returned to the Absorber. Treated gas from the absorption section enters the wash section at the top of the Absorber where EFG+ solvent in the vapor phase is captured by a circulating wash water loop. Wash water is drawn from the bottom of the wash section and sent through the Wash Water Cooler (3 0HKD50 AC001) by Wash Water Pump (30HKD40 AP001/2). Demineralized water make-up is added to the wash water loop.

The treated flue gas is then routed through a mesh mist eliminator and is returned to the stack of MPP3.

3.4.3 Solvent regeneration

The rich solvent leaves the bottom of the Absorber and is pumped by the Rich Solvent Pump (3 0HKG10 AP001/2) to the solvent regeneration section of the EFG+ Plant. It passes the Solvent Cross Exchanger (30HKG20 AC001-12) to heat the rich solution against the lean solution from the Lean Flash Drum (3 0HKH30 BB001). The hot rich solvent then enters the Stripper (30HKH10 BB0010).

Rich solvent flows down the Stripper through the packed beds counter-current to stripping steam, which liberates the CO_2 from the rich solvent. Solvent collects on the bottom chimney tray and is sent to the Reboiler (3 0HKH20 AC001-6). Heat input to the Reboiler is provided by condensing low pressure (LP) steam. In the wash section of the Stripper above the feed nozzle, water from the Overhead Accumulator (3 0HGA20 BB001) is used to wash out entrained solvent from the vapor stream. The resulting vapor from the top of the Stripper contains CO_2 saturated with water. The vapor is cooled and condensed by the Condenser (3 0HGA10 AC001/2) against vacuum condensate from MPP3, conserving the energy.

The two phase mixture from the Condenser enters the Overhead Accumulator where the carbon dioxide and condensed water are separated. The condensed water is pumped from the Overhead Accumulator by the Reflux Pump (3 0HGA30 AP001/2). A portion of the condensate is returned to the Stripper as reflux and the remaining liquid from the Overhead Accumulator is sent to the Absorber. The carbon dioxide rich vapor is sent to the CO_2 Compressor (3 0HGB10 AN001).

The lean solvent leaving the Stripper is sent to a Lean Flash Drum where it is flashed at near atmospheric pressure. The resulting flashed vapor is returned to the Stripper via the Lean Vapor Compressor (3 0HKH40 AN001). The lean solvent from the Lean Flash Drum is pumped by the Lean Solvent Pump (30HKG30 AP001/2) to the Solvent Cross Exchanger. After the Solvent Cross Exchanger, the lean solvent stream is routed back to the Absorber. A portion of the lean solvent stream is sent to the Carbon Bed (3 0HKF20 AT001). The filtered solvent returns to the main lean solvent line where it is returned back to the Absorber.

3.4.4 Solvent reclaiming

A slip stream of hot lean solvent from the bottom of the Stripper is taken out through a reclaiming package, originally designed to run discontinuously. This system was altered during the 2017 review because of new insights.

Originally a 20 wt% NaOH solution stream would be added to the reclaimer system. The recovered solvent would be sent back to the Lean Flash Drum. While this setup would work, the results from pilot plants suggested that the solvent purity should be kept to a higher standard than originally thought. With this in mind the solvent management package was redesigned to run continuously. The design was also changed in order to minimize the degradation of the solvent resulting from the reclaiming operation. With these changes the 2017 design would be able to keep the level of heat stable salts (HSS) in the solvent at a much lower level, without increasing the volume of the reclaimer waste stream.

The reclaimer waste is routed to the Reclaimer Waste Sump and periodically shipped off-site for disposal.

3.4.5 Solvent make-up and holding

Fresh solvent is stored in the Solvent Storage Tank (3 0HKJ20 BB001). Solvent make-up (normally no flow) can be injected into the lean solvent line when required. The solvent is sent from storage to the lean solvent line by Solvent Makeup Pump (3 0HKJ40 AP001) via Solvent Make-up Pump Suction Heater (3 0HKJ30AC001).

A Solvent Holding Tank (3 0HKJ50 BB001) is required to store the solvent inventory in the event of a scheduled maintenance or shutdown. The solvent can be transferred to the holding tank via the Lean Solvent Pump (to the Absorber) and Rich Solvent Pump (to the holding tank). After the maintenance or shut down is complete, the solvent in the holding tank can be transferred back to the Absorber using the Solvent Transfer Pump (3 0HKJ60 AP001).

3.4.6 CO_2 compression, oxygen removal, and dehydration

Following recovery, the CO_2 product must be compressed for transportation and purified to meet pipeline water and oxygen specifications. The CO_2 Product Compressor (3 0HGB10AN001) in the original design compressed the carbon dioxide to 129 bar(a), the pressure required for storage at field P18. During development of the project an alternative storage site was selected which caused some changes to the design.

This new field, Q16-Maas, is much closer to the power plant, and the pipeline route to the injection well is much easier to construct. Also, because this well was drilled and is being produced from an onshore installation, this opens up the opportunity to perform the final CO_2 compression close to the well. Flow assurance studies for site P18-4 had shown that the fact that the compressor and the well were separated by a long pipeline caused problems with control of the flow and formation of liquid CO_2 in the pipeline during shutdown. Flow into the well is best controlled by the temperature of the CO_2 at the wellhead, and the temperature is best controlled on the compressor.

This meant that compression would be split between the capture plant site and the site of the wellhead. In order to easily interface with existing infrastructure to deliver CO_2 to greenhouses the pipeline pressure was selected to be 20 bar. More on this subject can be found in the documents on Transport and Storage.

The CO_2 gas is cooled after each of the four compressor stages. Any condensed water is separated from the gas in knockout (KO) drums for each of the first three stages of compression.

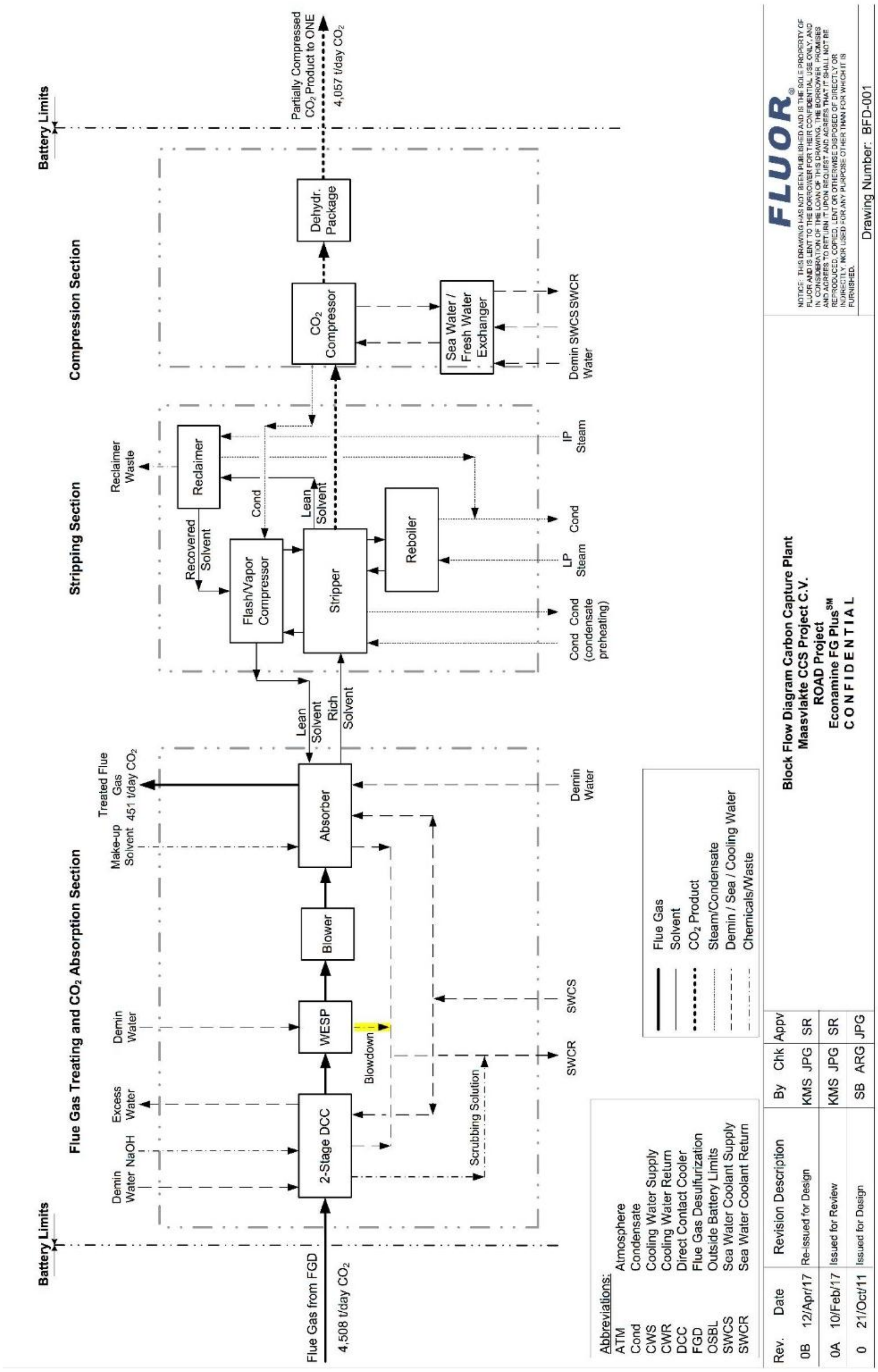
A CATOX Unit (3 0HGC10 BB001) was envisaged to be used to reduce the oxygen concentration to meet the pipelines specification. The CATOX Unit is a reactor containing a highly reactive catalyst that allows the safe and controlled combustion of hydrogen with oxygen, producing water which is knocked out after cooling. The required hydrogen gas would be procured and stored in gas cylinders. The gas leaving the CATOX Unit is cooled and partially condensed in the CATOX Aftercooler (3 0HGC20 AC001). Condensed water is then removed in the Water KO Drum (3 0HGC30 BB001). During an early stage of project development it became clear that the capture plant would be able to meet the pipeline specification without using the CATOX unit. It was therefore eliminated, but the freed up plot space was kept reserved for a CATOX unit in case of changes to the pipeline or the final destination of the CO_2.

Overhead gas from the CATOX aftercooler KO Drum is sent to the CO_2 Dehydration Package (3 0HGC40 AT001) to reduce the water content in the stream to below the required dew point. After dehydration the gas is routed to the battery limit for pipeline transportation. All water from the CO_2 Dehydration Package and water KO drums is combined and routed back to the Lean Flash Drum.

3.5 Process (block) flow diagrams

A block flow diagram of the capture plant and compressor is shown below (Figure 3.7).

Figure 3.7 Block flow diagram of the capture process and compression



In the Annex (Section 6.1), you will find the simplified process flow diagrams of capture plant and compressor.

3.6 Heat and mass balances

In Table 3.2 the heat and mass balances can be found on an overall level. The stream numbers correspond to the streams in the process flow diagrams in Section 6.1 (Annex).

Within the project more detailed but confidential stream compositions have been considered and those values served as input for the figures in the environmental impact assessment. Though limited, the streams in Table 3.2 give a good indication of the size and composition of the streams.

Table 3.2 Overall heat and material balance

Stream Description		Flue Gas to DCC		Neutralized Excess DCC Water		Demin Water		50 wt% NaOH		Scrubbing Solution Blowdown from DCC	
Stream Numbers		101		107		109 + 412		110		115	
Temperature, °C		48.2		46.6		15.0		20.0		27.8	
Pressure, bar(a)		1.00		4.00		1.21		1.21		5.33	
Component Flows	MW	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%
H_2O	18.02	3,489	11.2%	2,434	100.0%	13.5	100.0%	2	68.9%	17	95.0%
CO_2	44.01	4,268	13.7%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
N_2	28.02	22,086	70.9%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Ar	39.95	249	0.8%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
O_2	32.00	1,059	3.4%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
SO_2	64.06	0.44	14 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
NO_2	46.01	0.05	2 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
NO	30.01	0.96	31 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
NH_3	17.03	0.00	0.1 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
HCl	36.46	0.00	0.1 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
HF	20.01	0.01	0.2 ppmv	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Sodium Salts	-	0	0.0%	0.13	0.0%	0	0.0%	1.02	31.1%	0.89	5.0%
Ammonium Salts	-	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total Molar Flow, kgmol/hr		31,153		2,434		13.5		3		17.9	
Total Mass Flow, kg/hr		913,290		43,840		240		60		380	
Molecular Weight		29.3		18.0		18.0		24.8		20.7	
Density, kg/m³		1.099		989.7		999.5		1,528.1		1,159.7	
Liquid Flow, m³/hr				44.3		0.24		0.039		0.328	
Vapor Flow, $m^3_{i.N.}$/hr (dry)		621,606									
Vapor Flow, $m^3_{i.N}$/hr (wet)		700,000									
Vapor Flow, m³/hr (actual)		831,251									
pH				7.0		7.2		13.7		7.7	

Table 3.2 (continued) Overall heat and material balance

Stream Description		Treated Flue Gas to Power Plant Stack		Make-up Wash Water to Absorber		Low Pressure CO_2 to Compression		Compressed CO_2 Product		Reclaimer Effluent	
Stream Number		202		203		303		311		403	
Temperature, °C		30.4		15.0		40.0		24.0		114.5	
Pressure, bar(a)		1.00		1.01		1.65		23.00		1.00	
Component Flows	MW	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%	kgmol/hr	mol%
H_2O	18.02	1,110	4.5%	56	100.0%	183	4.5%	0	0.0%	-	-
CO_2	44.01	427	1.7%	0	0.0%	3,841	95.4%	3,841	99.9%	-	-
EFG+ Solvent	61.08	0	0.0%	0	0.0%	0	0.0%	0	0.0%	-	-
N_2	28.02	22,085	88.6%	0	0.0%	1	258 ppmv	1	271 ppmv	-	-
Ar	39.95	249	1.0%	0	0.0%	0	6 ppmv	0	6 ppmv	-	-
O_2	32.00	1,059	4.2%	0	0.0%	0	24 ppmv	0	25 ppmv	-	-
SO_2	64.06	0	0.0 ppmv	0	0.0%	0	0.0%	0	0.0%	-	-
NO_2	46.01	0.05	2.0 ppmv	0	0.0%	0	0.0%	0	0.0%	-	-
NO	30.01	0.96	39 ppmv	0	0.0%	0	0.0%	0	0.0%	-	-
CO	28.01	0.76	30 ppmv	0	0.0%	0	0.0%	0	0.0%	-	-
HSS	-	0	0.0%	0	0.0%	0	0.0%	0	0.0%	-	-
Total Molar Flow, kgmol/hr		24,931		56		4,025		3,842			
Total Mass Flow, kg/hr		701,310		1,000		172,350		169,020		40	
Molecular Weight		28.1		18.0		42.8		44.0			
Density, kg/m³		1.115		999.3		2.736		46.8		1,200.0	
Liquid Flow, m³/hr				1.00				389.6		0.035	
Vapor Flow, $m^3_{i.N.}$/hr (dry)		533,937				86,115		86,115			
Vapor Flow, $m^3_{i.N.}$/hr (wet)		558,805				90,216		86,115			
Vapor Flow, m³/hr (actual)		628,745				62,995		3,610			
pH				7.2							

3.7 Utility consumptions and productions

Table 3.3 sets out the utilities supplied to the capture plant. To allow Fluor to optimize their process, ROAD provided a set of approximate costs for some utilities. These costs are given in Table 3.4. Note that they include assumptions on input prices and the operational settings of the power plant, so they are specific to MPP3 and can also change with time.

Table 3.3 Capture Plant Utilities

Utility	Unit	Value
Sea Water		
Temperature inlet	°C	3-23
Max outlet temperature	°C	35
Flow	t/h	12 200
Low Pressure Steam		
Temperature	°C	227
Pressure	bar_a	3.0
Intermediate Pressure Steam		
Temperature	°C	tba
Pressure	bar_a	22.0
LP Condensate Return		
Temperature	°C	180
Pressure	bar_a	18.0
Pre-heat Condensate Supply		
Temperature	°C	26-36
Pressure	bar_a	19.0
Pre-heat Condensate Return		
Temperature	°C	70-100
Pressure	bar_a	16-18
Demineralized Water		
Temperature	°C	3-30
Pressure	bar_a	7
Flow (average)	kg/h	240
Potable Water		
Temperature	°C	<50
Pressure	bar_a	<7
Fire Water		
Temperature	°C	<30
Pressure	bar_a	<6
Electrical Power		
Voltage	kV	10.5
Frequency	Hz	50

Table 3.4 Indicative Costs of Utilities for Design Optimization

Utility	Unit	Value
Low Pressure Steam	€/t	8
Intermediate Pressure Steam	€/t	20
Demineralized water	€/m^3	3
Boiler feedwater	€/m^3	4
Electrical Power	€/MWh	55

3.8 Process performance data and CO_2 capture efficiency

The CO_2 capture efficiency of the ROAD plant is 90% at full load. Depending on operationals parameters selected, this can be maintained, and indeed exceeded, at part load.

Full performance data for the capture plant design conditions cannot be given for reasons of commercial confidentiality. Some aspects can be inferred from the overall heat and materials balance and the utility consumption data. However, details of the way Fluor have optimized performance of their process is a trade secret and is therefore omitted from public reports.

The single biggest costs are the use of electricity and steam by the capture plant. The steam supply from the power plant resulted in a loss of generating capacity, and ROAD compensated the power plant for this as a cost of lost electrical output. Therefore, for the purposes of assessing the overall system performance, a total electrical consumption can be used which is the sum of the electricity use, and the loss of generating capacity. This was estimated at 58.4 MW, of which just over half is due to steam consumption. It should be noted that this figure was not re-adjusted for the updated design developed in 2017. It is quite possible a small upward revision will be required due to additional compression costs of since the new design includes a less efficient air-cooled condenser stage at the Q16-Maas well location. The WESP would also increase utility consumption. The estimate includes all compression power, so the power for transport and storage is included as well. It also includes a margin of order 3 MW to allow for some periods with off-design operation, which can result in increased cost of steam because the power plant is at reduced load, or part load operation of the capture plant.

3.9 General plant layout drawings

The general arrangement of the capture plant was not substantially changed from the 2011 design (Ref 1). The original design layout is shown in Annex 6.5, for reference. This gives a simplified general arrangement drawing and a 3D perspective illustration. However, some adjustments were made to reflect the scope changes, principally the addition of the WESP. These were not fully engineered at the time the project stopped. Nevertheless the revised plot plan is shown in simplified form as Annex 6.2.

The principle changes from the 2011 layout are as follows:

- The CO_2 drying package has been moved to a new plot location just to the north of the existing plot. Because the high pressure compressor is now at the storage location, the drying package is the final stage of CO_2 processing before it is piped off-site so it no longer needs to be located close to the compressor. This move creates space next to the compressor for parts of the stripper system to move into. It also places the dryer in an area with space around it, so that future modifications to the drying package or additional CO_2 treatment (for example, for difference CO_2 use) can more easily be added
- The stripper system is moved towards the compressor building. This shortens the distance between the vacuum flash vessel and the lean vapour compressor, and also creates space at the north end of the plot for the WESP.

- The addition of an area for the WESP adjacent to the DCC and booster fan, in the space created by the move of the stripper system above.

3.10 Major equipment list and specifications

The major equipment is listed in the tables in this section (Tables 3.5-3.14), including sizing and material data and some relevant comments. These have been updated for the 2017 design including scope changes. Experieicne from the Wilhelmshaven pilot has been that corrosion is well controlled with the existing materials, provided the solvent is well managed. Hence changes to materials are very limited.

The tables are:

- Table 3.5 Blowers and Compressors
- Table 3.6 Heat Exchangers
- Table 3.7 Filters
- Table 3.8 Vessels
- Table 3.9 Pumps
- Table 3.10 Pumps (continued)
- Table 3.11 Sumps
- Table 3.12 Tanks
- Table 3.13 Speciality Process Equipment
- Table 3.14 Speciality Process Equipment (continued)

Table 3.5 Blowers and Compressors

Tag No.	Description	Motor Name plate	Size (LxW)	DN1/DN2	Metallurgy	Comments
		kW	m x m	mm		
3 0HKC10 AN001	Blower	2,250	15.6 X 4.0 + 2.5 X 1.6	(3250 x 2500) **/ 3370	316L SS with Carbon Ring Seals	Inlet Flowrate: 643,575 Nm3/hr **The inlet nozzle is rectangular.
	Blower Electric Motor Driver	-			-	
3 0HKH40 AN001	Lean Vapor Compressor	2,750	8.0 x 4.0	DN 600 / DN 600	316L SS with Carbon Ring Seals	
	Lean Vapor Compressor Electric Motor Driver	-			-	
3 0HGB10 AN001	CO_2 Product Compressor	12,000			316L SS	Inlet Flowrate: 90216 Nm3/hr Pressure Rise: 23.85 bar
	CO_2 Product Compressor Electric Motor Driver	-			-	

Table 3.6 Heat Exchangers

Tag No.	Description	TEMA Type or Plate Exch.	Size (per train)		Design Conditions				Metallurgy		Comments
					Shell/Hot (for Plate Type)		Tube/Cold (for Plate Type)				
			L m	W / D m	Pres bar(g)	Temp °C	Pres bar(g)	Temp °C	Shell/Frame	Tube/Plate	
3 0HKB30 AC001/2	DCC Water Cooler	Plate			6.5	90	6.5	90	CS	Titanium	
3 0HKD30 AC001	Absorber Intercooler	Plate			6.5	90	6.5	90	CS	Titanium	
3 0HKD50 AC001	Wash Water Cooler	Plate			9.0	90	9.0	90	CS	Titanium	
3 0HKG20 AC001-4	Solvent Cross Exchanger	Plate			12.0	140	12.0	140	CS / 316L	316L SS	
3 0HGA10 AC001/2	Condenser	BXU			30.0	160	38.0	160	CS / 304L cladding	316L SS	
3 0HKH20 AC001-4	Reboiler	Plate			5.0/FV	180	5.0/FV	180		316L SS	
3 0HGC20 AC001	CATOX Aftercooler	AHU			30.0	125	24.0	125	316L SS	316L SS	
3 0PGF30 AC001	Sea Water / Fresh Water Cooler	Plate			6.5	80	6.5	80	CS	Titanium	

Table 3.7 Filters

Tag No.	Description	Design Conditions		Metallurgy	Comments
		Pres bar(g)	Temp °C		
3 0HKF20 AT001	Carbon Bed	12.0	140	316L SS	
3 0HKH80 AT001	Desuperheating Condensate Filter	25.0	180	316L SS	Inlet Flow Rate: 20.4 m^3/hr. Diameter: DN 200
3 0PAC50 AT001	Cooling Water Mussel Filter	6.5	80	Duplex	Inlet Flow Rate: 11930 m^3/hr. Diameter: DN 1200

Table 3.8 Vessels

Tag No.	Description	Dimensions		Design Conditions		Metallurgy	Comments
		Diameter	T/T	Pres	Temp		
		m	m	bar(g)	°C		
3 0HKB10 BB001	Direct Contact Cooler	10.7	23.9	0.14/-0.2	125	CS / 304L SS cladding	
3 0HKD10 BB001	Absorber	12.8	43.4	0.14	125	CS / 304L SS cladding	
3 0HKH10 BB001	Stripper	7.8	29.8	3.5/FV	160	Duplex	
3 0HGA20 BB001	Overhead Accumulator	3.3	5.8	3.5/FV	125	CS / 304L SS cladding	
3 0HKH30 BB001	Lean Flash Drum	7.8	12.8	3.5/FV	160	CS / 304L SS cladding	
3 0HKH60 BB001	Reboiler Condensate Drum	1.9	5.4	5.0/FV	180	CS	
3 0HGC30 BB001	Water KO Drum	1.7	3.75	30.0/FV	125	316L SS	

Table 3.9 Pumps

Tag No.	Description	Pump Type	Motor Name plate	Metallurgy		DN1/DN2 (Note 1)	Comments
			kW	Impeller	Casing	mm	
3 0HKB20 AP001/2	DCC Circulation Pump	Centrifugal	250	316L SS	316L SS	DN 450 / DN 400	One operating pump with one spare.
3 0HKE70 AP001/2	DCC Scrubbing Solution Pump	Centrifugal	90.0	316L SS	316L SS	DN 300 / DN 300	One operating pump with one spare.
3 0HKB60 AP001/2	DCC Excess Water Pump	Centrifugal	15.0	12% Cr	CS	DN 100 / DN 80	One operating pump with one spare.
3 0HKE60 AP001/2	DCC NaOH Injection Pump	Positive Displacement	0..1	316L SS	316L SS	DN 50 / DN 50	One operating pump with one spare.
3 0HKE30 AP001/2	50 wt% NaOH Pump	Centrifugal	0.2	12% Cr	CS	DN 50 / DN 50	One operating pump with one spare. S-6.
3 0HKE10 AP001	NaOH Fill Pump	Centrifugal	2.5	12% Cr	CS	DN 50 / DN 50	Normally not running. S-6
3 0HKD20 AP001/2	Absorber Intercooler Pump	Centrifugal	160	316L SS	316L SS	DN 400 / DN 400	One operating pump with one spare.
3 0HKD40 AP001/2	Wash Water Pump	Centrifugal	160	316L SS	316L SS	DN 300 / DN 250	One operating pump with one spare.
3 0HKG10 AP001/2	Rich Solvent Pump	Centrifugal	600	316L SS	316L SS	DN 500 / DN 350	One operating pump with one spare.
3 0HGA30 AP001/2	Reflux Pump	Centrifugal	11.0	316L SS	316L SS	DN 100 / DN 80	One operating pump with one spare.
3 0HKG30 AP001/2	Lean Solvent Pump	Centrifugal	480	Super Duplex	Super Duplex	DN 500 / DN 350	One operating pump with one spare.
3 0HKH70 AP001/2	Reboiler Condensate Pump	Centrifugal	125	12% Cr	CS	DN 150 / DN 100	One operating pump with one spare.

Table 3.10 Pumps (continued)

Tag No.	Description	Pump Type	Motor Name plate	Metallurgy		DN1/DN2 (Note 1)	Comments
			kW	Impeller	Casing	mm	
3 0HKJ10 AP001	Solvent Fill Pump	Centrifugal	4.0	316L SS	316L SS		Normally not running.
3 0HKJ40 AP001	Solvent Make-up Pump	Centrifugal	0.7	316L SS	316L SS		Normally not running.
3 0HKE80 AP001/2	Neutralization NaOH Injection Pump	Positive Displacement	0.01	316L SS	316L SS		One operating pump with one spare.
3 0HKK20 AP001	Solvent Sump Pump	Vertical	2.0	316L SS	316L SS		Normally not running.
3 0HKJ60 AP001	Solvent Transfer Pump	Centrifugal	7.0	316L SS	316L SS		Normally not running.
~~3 0HKF40 AP001~~	~~Reclaimer NaOH Injection Pump~~	~~Positive Displacement~~	~~0.55~~	~~316L SS~~	~~316L SS~~		~~One operating pump.~~
3 0PAC50 AP001/2	Sea Water Coolant Pump	Centrifugal	1,600	Super Duplex	Super Duplex	DN 1200 / DN 900	One operating pump; one spare rotor.
3 0PGF20 AP001/2	Fresh Water Coolant Pump	Centrifugal	160	12% Cr	CS		One operating pump with one spare.
3 0HKE96 AP001	Chemical Sump Pump	Vertical	1.0	316L SS	316L SS		One operating pump.
3 0HKE85 AP001/2	WESP flushing water Pump	Vertical	11.0	Alloy 20	Alloy 20		One operating pump with one spare.
3 0GUA20 AP001	Storm Water Sump Pump	Vertical	2.5	12% Cr	CS		One operating pump.

Table 3.11 Sumps

Tag No.	Description	Dimensions			Metallurgy	Comments
		Length m	Width m	Depth m		
3 0HKK10 BB001	Solvent Sump	3.3	3.3	4.0	316L SS tank in concrete sump	Located below grade. Design Temperature: 160 °C Design Pressure: 40 mbar(g)
3 0HKE92 BB001	Chemical Sump	3.7	3.7	4.0	316L SS tank in concrete sump	Located below grade. Design Temperature: 125°C Design Pressure: 20 mbar(g)
3 0HKF90 BB001	Reclaimer Waste Sump	3.5	3.5	2.2	316L SS tank in concrete sump	Located below grade. Design Temperature: 170 °C Design Pressure: 40 mbar(g)
3 0GUA10 BB001	Storm Water Sump	10.0	9.0	4.0	Concrete sump	Located below grade.
3 0GNK10 BB001	Oily Water Sump	4.0	4.0	4.0	Concrete / 316L SS lining.	Located below grade.

Table 3.12 Tanks

Tag No.	Description	Dimensions		Metallurgy	Comments
		Diameter	T/T		
		m	m		
3 0HKJ20 BB001	Solvent Storage Tank	4.0	5.4	1.4362	Blanketed with Nitrogen.
3 0HKE20 BB001	50 wt% NaOH Storage Tank	4.0	4.8	CS	Tank to include 50 wt% NaOH Storage Tank Heating Coil 3 0HKE25 AC001.
3 0HKB50 BB001	DCC Water Neutralization Tank	3.7	4.9	CS	
3 0HKJ50 BB001	Solvent Holding Tank	10.7	14.2	1.4362	
3 0HKE50 BB001	20 wt% NaOH Storage Tank	1.2	1.4	CS	
3 0HKE75 BB001	WESP Flushing Water Tank	2.3	3.2	Epoxy FRP	
3 0PGF10 BB001	Circulating Water Expansion Tank	0.6	2.0	316L SS	

Table 3.13 *Speciality Process Equipment*

Tag No.	Description	Comments
3 0HKJ30 AC001	Solvent Make-up Pump Suction Heater	Electric heater with heat rate of 143 kW. CS / 304L SS cladding.
3 0HKH50 BN001	LP Steam Desuperheater	Materials of construction are as per manufacturer's standard.
3 0HGC40 AT001	CO_2 Dehydration Package	Reduces water content of product CO_2 to < 150 ppmv. MOC: per vendor standard; minimum 304L SS at wet end.
3 0SCA10 AN001	Instrument and Plant Air Package	Includes instrument air compressor and dryer (2x 100%). Estimated capacity is 750 Nm^3/h. Supply pressure of 7 bar(g) at -20°C dewpoint. MOC: TBD
3 0HKE25 AC001	50 wt% NaOH Storage Tank Heating Coil	To be purchased as integral part of the 50 wt% NaOH storage Tank (3 0HKE20 BB001). MOC: alloy 625 with CS mounting flange.

Table 3.14 Speciality Process Equipment Continued

Tag No.	Description	Comments
3 0HGC10 BB001	CATOX Unit	CS / 304L SS Cladding. Reduces Oxygen content of product CO_2 to < 10 ppmw.
3 0HKE65 AT001	Wet Electrostatic Precipitator	90% removal of H_2SO_4 aerosol particle count as measured by ELPI+ device.
3 0PGF15 AK001	Cooling Water Treatment Package	Treatment package for circulating fresh water loop. Circulating fresh water flow rate = 1,376 m3/hr.
3 0PAC50 AK001	Sea Water Priming Package	Vacuum priming system.
3 0HKC10 BS001	Blower Silencer	
	Solvent Package	Multiple proprietary equipment items for separation of degredation products and recovery of solvent.

3.11 CO_2 specifications (P, T, purity) for transport

The updated design conditions for CO_2 export pipeline from the compression plant is given in Table 3.15. This covers the pipeline design and CO_2 purity requirements. The dryness specification was relaxed compared to the P18-4 design (For P18, the requirement was $H_2O<50ppm_v$). This is because the Q16-Maas reservoir is higher pressure, and therefore the risk of cold temperatures due to Joule Thompson cooling is much lower. Drying the CO_2 to 150 ppmv is sufficient to prevent water condensation anywhere in the proposed transport and storage system for Q16-Maas for the lowest foreseen pressures and temperatures.

Oxygen is only corrosive in the presence of liquid water. Since this is prevented, there is no requirement to specifically remove oxygen from the CO_2. The oxygen limit is the specification was based on the level the capture plant process would naturally deliver.

Table 3.15 Pipeline Design and Operating Conditions for Q16-Maas

Maximum design pressure:	44	barg
Maximum operating pressure ROAD	22	barg
Normal operating pressure range	19-22	barg
Minimum operating pressure	1	barg
Minimum design temperature	-10	°C
Maximum design temperature	50	°C
Maximum operating temperature	40	°C
Minimum operating temperature	0	°C
Technical Design Life	30	years
Cover depth in pipeline corridor	1	m
Cover depth for crossing pipeline corridor	2.5	m
CO_2 properties		
Purity	>99%	
H_2O	<150	ppm_v
O_2	<70	ppm_v

In addition to the components given in Table 3.15, The CO_2 will also contain nitrogen and argon, which are inert, and trace quantities of degradation products from the solvent (mostly acetaldehyde) which do not pose a problem for geological storage. The CO_2 is expected to be greater than 99.9% pure in practice.

3.12 CO_2 Metering and analysis. Approach, locations, technology

One of the main differences between CO_2 and other substances is the fact that its phase-transitions are very close together and lie around ambient conditions:

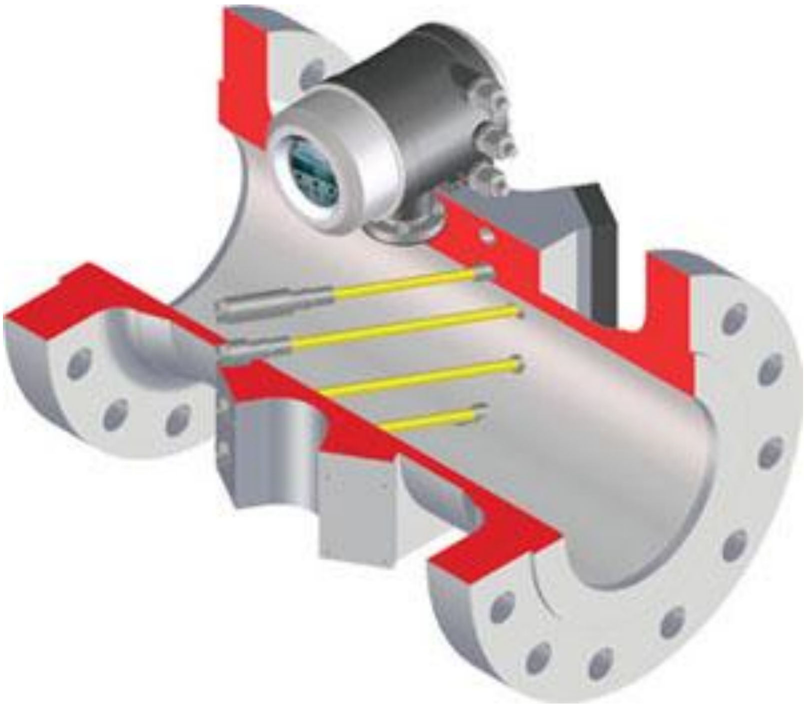
- The CO_2 critical point is close to ambient and normal gas transportation conditions (P_c = 73.773 bar, T_c = 30.978 °C)
- The behaviour of the fluid around the critical point is very sensitive to pressure and temperature variation. All mechanical properties are strongly affected by the transition around the critical point.
- If the CO_2 flow is intermittent, this will allow the gas to cool down and cause liquid to pool

This can make CO_2 very difficult to control and measure. In our project the operational conditions are close to the two-phase line (liquid+gas line) of CO_2, especially during the start-up phase.

Furthermore, the three most-suited measuring technologies suffer from a number of difficulties, either specific to CO_2, or associated with this possible presence of liquid. Therefore we could dismiss the turbine flow meter immediately and only looked at ultrasonic flow meters and the Coriolis flow meter.

Ultrasonic (US) flow meters are based on the principle of transit-time measurement, which yields a fluid velocity. Figure 3.8 shows a cut-out of such a flow meter with the ultrasonic beams shown in yellow. Being a volumetric device, the measured volume will have to be converted to a mass flow through the use of an equation of state (describing the relationship between pressure, temperature, volume and mass), if it were to be used for custody transfer purposes. This introduces numerical problems, as the equations of state cannot be solved around the gas's critical point.

Figure 3.8 Ultrasonic Flow Meter



US flow meters are widely used nowadays in natural gas custody transfer metering stations and give very good results, even at pressures up to 450 bar and temperatures between -200°C and 60°C (optionally even higher). However, sensor types and the frequencies for (dense) gas are different from those for liquid measurements.

When it comes to measuring CO_2, none of the suppliers of US metering devices had ready-made solutions. SICK was the only company on the market (in 2012) claiming that they had successfully tested natural gas with high concentrations of CO_2. Some tests evaluating the attenuation of ultrasonic signals in supercritical CO_2 had also been conducted by SICK for E.ON. No tests however on actual flow, in real flowing conditions, has been conducted up to then. No references were available for CO_2 measurements with US meters.

The presence of liquid would not be picked up by a US transducer, and it would probably upset the correct operation of a US meter designed for (dense) gas. The effect can be summarized by assuming the Inside diameter will be reduced by the presence of the liquid, which will consequently produce measurement errors. One positive point comes from the fact that the US flow meter can be constructed at the same size as the line and would therefore not introduce any extra pressure drop.

However, as the accuracy of this method depends on a laminar, undisturbed flow field at the location of the measurement, these types of devices require a long stretch of straight-run pipe before and after the measuring section: up to 10D upstream, and another 5D downstream of the measurement, and 3 to 5D additionally for the measurement itself. This lead to concerns about whether the total required length would fit onto the offshore injection platform.

The Coriolis meter is a (direct) mass flow meter. It functions by measuring the influence of the medium on the vibration of a curved piece of pipe carrying that medium. The curved pipe is made to vibrate, and the resulting amplitude and frequency give information on the mass flow and density inside the pipe. As it's a direct mass flow measurement, this means that there is no need for conversion or recalculation with an equation of state. The Coriolis meter is also not affected by the type of fluid, presence of aerosols, particles etc. It can measure gas, dense phase, as well as liquid phase. When two-phase flow is present, this does affect the accuracy of the measurement and it would probably mean the measurement result would not reach the accuracy requirements for custody transfer in that case.

The accuracy of the Coriolis meter increases with the speed of the fluid. This is one of the reasons the intended supplier Emerson proposed a meter with a smaller line size. The other reason to choose a smaller size, or rather a number of smaller sized measurements, is the fact that the price of this device rises exponentially with the line size. This is illustrated by Figure 3.9, that probably shows a 6 inch measurement. A large line size means that a big piece of pipe, and its contents, must be made to vibrate; resulting in a very big driver. This problem is compounded by the fact that the design-pressure of the CO_2 pipeline is very high, which means thick-walled components and even more mass to be put in motion

Figure 3.9 Coriolis Flow Meter (probably a 6 inch meter, available up to 12 inch, DN300)

4. Health, Safety and Environment

4.1 Introduction

This section reports the environmental impact based on the design developed in 2012, and the associated permit documents. The engineering update of 2017 did not reach sufficient detail for an updated environmental impact assessment to be produced, nor for updated safety assessment (HAZID and HAZOP). Changes were expected to be minor, and to be environmentally neutral. This section therefore presents data that has already been published either in Environmental Impact Assessment (in Dutch, Ref 9) or in the non-confidential FEED Study (Ref 1).

Since the project never reached the construction phase, the focus for safety was ensuring a design that could be constructed and operated safely. To that end, this section gives the hazardous area diagrams and a summary of the outcome of the HAZID/HAZOP performed. The HAZOP review process was not completed.

4.2 Environment: air emissions, waste water, solid waste

This section describes the environmental emissions of the capture plant of the ROAD project. The information is based on the Environmental Impact Assessment (EIA) submitted by in June 2011 (Ref 9). In the EIA more detailed information on the emissions and noise can be found. The Material Safety Data Sheets (MSDS) of sodium hydroxide and monoethanol amine (MEA) can be found in Annex 1 of Ref 1.

4.2.1 Emissions to Air

In the capture installation circa 23% (volume) of the flue gases from MPP3 will be treated. The treated flue gas will be sent back to the stack of MPP3, where it will naturally mix with the remainder of the flue gases of MPP3 and be emitted to air by the existing stack of MPP3.

Three relevant operating modes are described to be able to calculate the environmental impact:

- Operating mode 1. MPP3 operational without the CCS installation.
- Operating mode 2. MPP3 full load, CCS fully operational, circa 23% of flue gas treated
- Operating mode 3. MPP3 part load, all flue gas treated in CCS installation. Concentration will change, but environmental load stays equal.

In Table 4.1 and 4.2, the permitted composition of the flue gas is stated.

Table 4.1 Assumptions for composition of flue gas from MPP3

Component	**Flue gas MPP3 (worst-case) (current situation, operating mode 1)**		**Part of Flue gases to capture plant**	
	Concentration [mg/Nm^3]^1	Load [kg/hour]	Concentration [mg/Nm^3]^1	Load [kg/hour]
NH_3	0,1	0,3	0,1	0,1
NOx as NO_2	65,0	220	65^2	45,5
SO_2	40,0	115	40	28,0
HCl	3,0	9,0	3,0	2,1
HF	0,4	1,3	0,4	0,3
CxHy	1,0	3,0	1,0	0,7
Dust	4,0	11,7	4,0	2,8
CO_2	-	857.000	-	188.000
Flue gas specifications				
Temperature (K)	324		321	
Water (vol%)	11,2		11,2	

O_2 (vol%)	3,4	3,4
CO_2 (vol%)	13,7	13,7
N_2 (vol%)	70,9	70,9
Flow (Nm^3/hour)	3.190.000	700.000

[1]based on dry conditions, 6% Oxygen; [2]: 4 – 5% NO_2;

Table 4.2 Assumptions for composition of emitted flue gas with carbon capture in operation

Component	**Operating mode 3** **Part load**		**Operating mode 2** **Full load**	
	Concentration [mg/Nm^3]	Load [kg/hour]	Concentration [mg/Nm^3]	Load [kg/hour]
MEA	11	6,2	2,0	6,2
NH_3	5	2,8	1,0	3,1
NOx as NO_2 [1)]	77,6	44,0	70,0	215,0
SO_2	0	0	31	95,0
HCl	3,7	2,1	2,9	9,0
HF	0,5	0,3	0,4	1,3
CxHy	23	13	10	31
Dust	2	1,1	3,3	10
CO_2	-	18.000	-	687.000
Flue gas specifications				
Temperature (K)	308		321	
Water (vol%)	5,7			
CO_2 (vol%)	1,7			
O_2 (vol%)	4,2			
Flow (Nm3/hour)	566.000		3.056.400	

1) NO_2 based on 5% of NO_x

In the Table 4.2, the emissions of Operating mode 2 (full load) and 3 (part load) are indicated. The emissions at part load are equal to the emissions at the outlet of the capture plant. The emissions at full load are representative for the combined stream of flue gases where a part is treated in the capture plant. The emissions are based on a yearly average value.

4.2.2 Emissions to Water, and water use.

A full account of the water balance for the 2012 ROAD design is given in Ref 3.

Process water

During capture of CO_2 process water is released in a number of places.

In the first place, at normal operation, approximately 40-50 m^3/hour of condensate water is released from the flue gas pretreatment. This process water arises from cooling of the saturated flue gas. This water can be used in the flue gas desulphurisation.

The flue gases are further desulphurized by the use of a sodium hydroxide solution. The sulphur compounds react with this liquid and are removed with a surplus of water. Per hour approximately 0,3 m^3 of this kind of process water is produced containing sulphate salts.

Cooling water

In the capture process cooling water is used for several cooling steps. The incoming flue gas is cooled. In the absorber the washing water is cooled, and the pumps, fans and compressor need to be cooled as well.

The cooling water intake of MPP3 has to conform to the current permit of 120.000 m^3/hour of which the capture installation would need a maximum of 15.000 m^3/hour. The cooling water is sea water. By raising the temperature difference between cooling water inlet and outlet, the mass flow of the cooling water would remain constant.

Demineralized water

In the capture process demineralized water is required to dilute stock solutions of sodium hydroxide and solvent. Demineralized water is also used in the final water wash of the flue gases at the outlet of the absorber. The demin. water will be supplied by MPP3. The amount necessary will on average be less than 2 m^3/hour.

Waste

The solvent degrades over time and needs to be regenerated continuously. In this process a part is removed as waste. This waste stream is maximum around 500 tonnes/year and is considered as chemical waste. As soon as the capture plant is operational the waste stream will be analysed to check if this consideration is correct. This chemical waste will be disposed of by a waste treatment company.

4.2.3 Other Chemicals

In the capture process several chemicals are used. These are listed in Table 4.3 below.

Table 4.3 Other Chemicals

Chemical	Consumption
Sodium hydroxide (50% in water)	1.000-1.500 kg/day
Solvent	500-1.000 kg/day
Hydrogen (only if CATOX is used)	100-300 Nm^3/day
Nitrogen	1.000-2.000 Nm^3/day
Activated carbon	50-100 ton/year

4.2.4 Noise

The design of the capture plant has been examined with regards to noise emissions. All the components that produce noise, like pumps, fan and compressor have been added to the existing acoustic model of MPP3. The additional noise fits within the permited noise limits.

4.3 Environmental Impact Assessment Summary

The ROAD project was a first of its kind. Therefore the permitting process was quite interesting. First, the project team had to find out which permits were to be applied for. The FEED study results were used as input for the permit application, as the required emission values could not be based on measurements on existing installations.

The entire permitting procedure for the ROAD project lasted more than three years from the formal submission of permits. In June 2011, ROAD submitted the Environmental Impact Assessment (EIA) and all permit applications (including capture). Half a year later, the competent authorities published the permit applications, the EIA and the draft permits (capture in October 2011). After a number of public town hall meetings and the formal appeal period the final capture permit was published in April 2012 and became definitive six weeks later as no appeals were put forward by stakeholders.

For the capture plant the following permits had to be obtained:

- All-in-one permit for physical aspects;
- Water permit;
- Nature Protection Act 1998 permit;

- Emission permit.

In May 2012 all capture permits (except for the emission permit that would be submitted in 2014) became definitive and irrevocable (no more court procedures).

The following table (Table 4.4) gives an overview of the environmental impact of the capture plant as described in the EIA. The overall conclusion is that the capture plant has no or neglible negative environmental impact.

Table 4.4 Overview of environmental impact of carbon capture

Theme	**Aspect**	**Case**
		Base case
Soil	Soil quality	0
Water	Groundwater	0
	Cooling water	-
	Waste water	0
	Regenwater	0
Nature	Protected areas (land)	-
	Protected species (land)	-
	General species (land)	0
Noise	Direct nuisance	-
	Indirect nuisance	0
Air	Air quality	-
	Deposits: eutrophication	-
	Deposits: acidification	+
	CO_2 reduction	++
External safety	External impact and domino effects	0
	Individual risk	- -
	Societal risk	-
Landscape	Visual impact	0
Trafffic	Vehicle movements	-
Waste	Hazardous waste	--
	Residues	-
Energy	Cooling water	--
	Steam + Power	--

For the assessment of the environmental impacts a benchmark is being used. This benchmark consists of a seven-point scale which values impacts from extensive positive (+++) to extensive negative (- - -). The benchmark can be visualized with the following color table (Table 4.5).

Table 4.5 Colour coding definition for Table 5.4

+++	Extensive positive impact: development has added value
++	Substantial positive impact: clear improvement compared to the reference situation
+	Negligible positive impact: no improvement
0	No impact
-	Negligible negative impact: no disturbance
--	Substantial negative impact: mitigating measures need to be researched
---	Extensive negative impact: effect outside regulatory framework (development is not possible)

4.4 Hazardous Area Diagrams

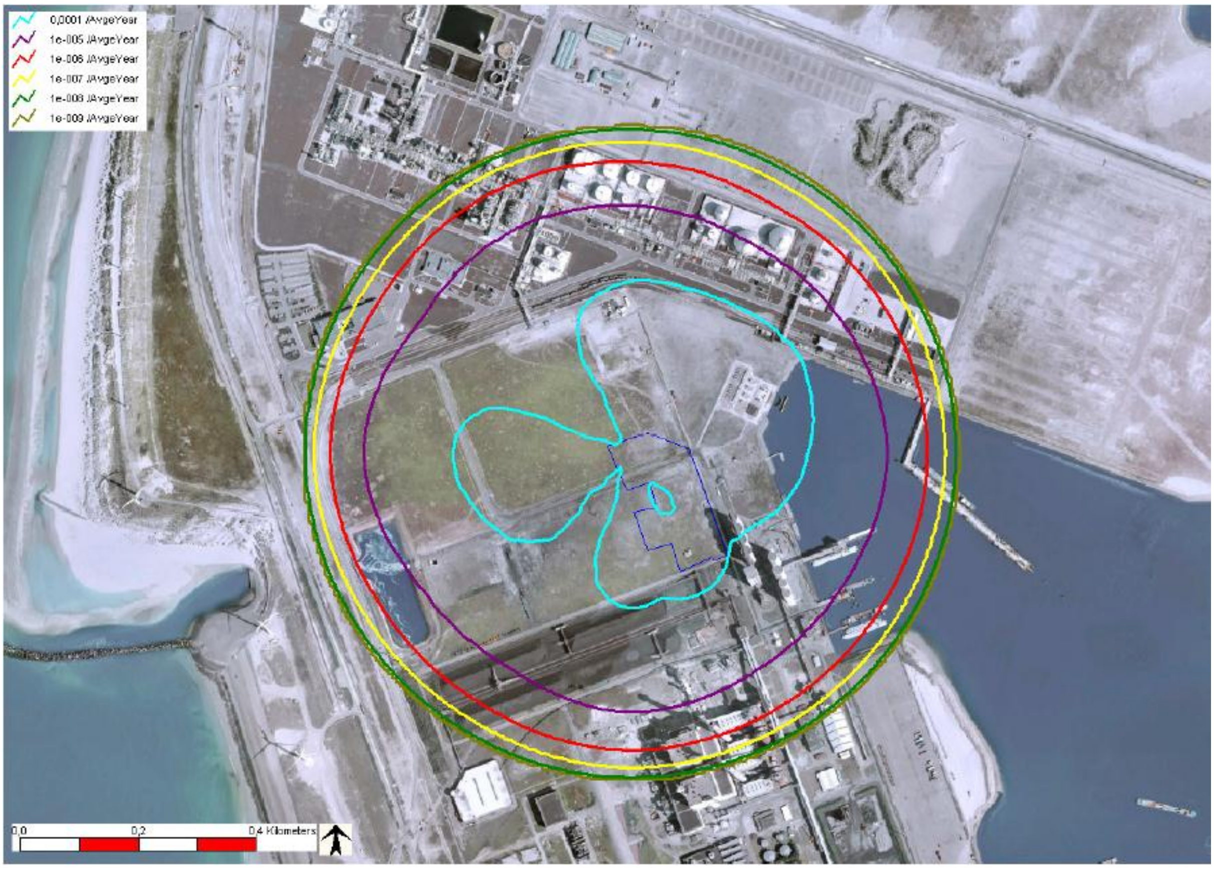
Within the context of the EIA a risk analysis was conducted concerning the capture plant to be located on the site of the Maasvlakte Power Plant 3. The capture plant was assessed against present and future regulations. In case of uncertainty on future regulation or calculation methods for quantative risk analysis, conservative assumptions were taken into account in order to mitigate these uncertainties. Possible external influences on the capture plant were also verified. The risk is expressed as “chance that a person, who remains in the area continuously and unprotected, dies as a result of an accident with dangerous substances doing a risky activity”.

Based on the calculations and the analysis the following conclusions were drawn:

- The individual risk contour of 10^{-5} chance per year lies inside the MPP3 site boundary. Within the individual risk countours of 10^{-6} per year no offices or other objects are located according to which the presence of persons is to be expected. In the future, installations could be developed to the northside of the capture plant.
- Within the individual risk countours of 10^{-6} per year no vulnerable or limited vulnerable objects are located. Therefore, the capture plant meets requirements set by external safety regulations.
- The societal risk of the capture plant stays below the specified orientation value as set by external safety regulations. In case the planned construction of the capture plant will be realized the competent authority will be accountable for the societal risk.
- The applied probit relation will not lead to an underestimation of the risks of the capture plant. The calculation method used in this risk analysis adresses the specific characteristics of CO_2. Therefore, this calculation method will not result in an underestimation of the risks of the capture plant.

The risk contours are shown in Figure 4.1.

Figure 4.1 Individual risk countours of capture plant



4.5 Summary of HAZOP/HAZID

HAZID (HAZard IDentification) is a technique for early identification of potential hazards and threats. A HAZID identifies and assesses hazards leading to major incidents or accidents, which provide essential input to project development decisions and early identification of required additional studies. This will lead to safer design options being adopted with a minimum cost of change penalty.

4.5.1 HAZID Methodology

The HAZID technique is:

- A means of identifying and describing hazards and threats at the earliest practicable stage of a development or venture.
- A meeting employing a highly experienced multi-discipline team using a structured brainstorming technique, based on a checklist of potential HSE issues, to assist in identifying and assessing potential hazards.
- An identification and description process only, not a forum for trying to solve potential problems.

Many of the hazards and HSE issues are generic for a whole development and are not specific to any part of the plant or location. The typical procedure is therefore firstly to apply the technique to the whole project as a single entity. The study method is a combination of identification, analysis and brainstorming based on guidewords listed in a checklist. The guidewords are divided into three main sections:

- Section 1: external and environmental hazards;
- Section 2: facility hazards; and

- Section 3: health hazards.

Two of the sections (1 and 3) contain overall hazards and project implementation issues which are applicable to the project as a whole. The facility hazards (2) can be identified for separate units or functional blocks of the process and utilities.

4.5.2 Results and Follow Up

The HAZID resulted in a total of 20 action items of which 17 were to be resolved during FEED. The following table (Table 4.6) gives an overview of all action items, and the responses from the action party.

Table 4.6 HAZID Results

No:	Description:	By:	Due:	Response:	By:	Date:
1	Determine what the limit value is for amine in stormwater according to Dutch regulations	Fluor HSE	1-Jul	No set level exists for amine. IPPC Reference Document on Best Available Techniques in Common Waste Water and Waste Gas Treatment / Management Systems in the Chemical Sector gives limit for Chemical Oxygen Demand of 30-250mg/l. Final emission limits will be set in Environmental permit	O. Schot	5-Jul-10
2	Investigate whether REACH Directive does require a risk assessment for amine	Fluor HSE	1-Jul	Pre-registration for amine has been submitted. No risk assessment required	O. Schot	5-Jul-10
3	Verify whether design is in accordance with Eon ATS 7 document	Fluor Project	15-Jul	All client specs will be reviewed by SC and deviations will be advised to the JV. The first day of Meeting # 5 with the JV will be used to review all Fluor comments / deviations to the specifications. This action item will therefore automatically be closed out	R. Naafs	5-Jul-10
4	Consider to merge smaller foundations into one larger piled foundation whenever practical	Fluor CSA	1-Jul	Small foundations are placed on a common mat	A. Marfatia	22-Jul-10
5	Consider to apply measures to protect existing cooling water channels	Fluor CSA	1-Jul	The current design location of the foundations are not closely located to the existing cooling water channels. This should be evaluated further during the EPC with the final geotech consultant.	L. Chiu	27-Jul-10
6	Provide the relevant parts of EIA (MER) to Fluor. Masterplan brandveiligheid MPP3	JV Project	15-Jun	The EIA of MPP3 does not contain items that are relevant to the capture plant except the “masterplan brandveiligheid MPP3”, which was provided.		
7	Discussions with authorities need to be opened to discuss impact of capture plant on operating permit, with respect to	JV Project	EPC	Discussions with the authorities have started but results regarding impact of emission on operation permit will take a long time. Resolution by JV to continue in EPC.		

No:	Description:	By:	Due:	Response:	By:	Date:
	emissions					
8	Provide the Masterplan Brandveiligheid MPP3 to Fluor	JV Project	15-Jun	Received by Fluor.	O. Schot	5-Jul-10
9	Consider to apply protection barriers at equipment close to the road	Fluor CSA	01-Jul	We have included in the material takeoff (50 Guard Posts), some of which can be used for equipment barrier protection throughout the CO_2 plant.	H. Chang	27-Jul-10
10	Capture plant and MPP3 operators to be trained regarding emergency response planning	JV operations	EPC			
11	Verify design, including design temperature, of system from compressor to stack to ensure depressurization of compressor can be done taking auto-refrigeration and mixing effects with flue gas into account	Fluor Process	1-Jul	Depressurization done with manual valves in two stages from high to intermediate and intermediate to low. Fluor to confirm with compressor vendor to finalize settle-out pressure and depressurization strategy. P&IDs shall be clarified and all depressurization lines to be traced.	J. Gilmartin	5-Jul-10
12	Verify that overfilling of the 20% caustic tank due to static head from the 50% caustic tank can not occur	Fluor process	1-Jul	Line from 50% tank to 20% tank will run up through pipe rack. Specified high point on P&IDs.	J. Gilmartin	5-Jul-10
13	Measures should be taken to avoid galvanic corrosion when stainless steel meets carbon steel	Fluor Piping material	1-Jul	Galv Corrosion occurs between Stainless(SS) and galv. carbon steel(CS). Where there is a connection between the two materials an INSULATING SET is provided to prevent conductivity. Where a SS pipe is being supported, galv. steel will not be used.	K. Vo	22-Jul-10
14	Ensure control room is upwind or cross wind of prevailing direction	Fluor Piping	1-Jul	The prevailing wind is from the southwest which makes the control building location in the crosswind direction.	D. Muriilo	22-Jul-10
15	Verify Technical Specification on requirement for deluge system on lube oil system	Fluor HSE	1-Jul	Technical specification does not require deluge system on lube oil system.	O. Schot	5-Jul-10
16	Ensure adequate escape routes from control room	Fluor CSA	July 15th	Secondary escape route from Control room has been added on the evacuation plan and will be added in the final FEED drawings.	A. Marfatia	22-Jul-10

No:	Description:	By:	Due:	Response:	By:	Date:
17	Consider portable CO_2 detection in the CO_2 handling and detection concept	Fluor HSE	July 15th	Fixed CO_2 detection is foreseen for all buildings/enclosures that could be subject to elevated CO_2 concentrations. Outdoor acoustic leak detection is foreseen for leaks in the high pressure CO_2 system. Therefore no portable CO_2 detection is deemed required.	O. Schot	5-Jul-10
18	Fire water demand for capture plant needs to be determined. JV then confirms availability of firewater from MPP3 system	Fluor HSE	15-Jul	Firewater demand is determined and documented in A4NA-0312-53-RP012, Fire Protection Concept	O. Schot	5-Jul-10
19	Ensure sufficient flush medium available and handling capacity for absorber and stripper	Fluor Process	1-Jul	We would fill the absorber/stripper system with demin water from the initial fill line. The amount of demin water needed is equal to the solvent system inventory (estimated at 923 m3). If this amount of water is not available, then water would need to be provided by water trucks.	J. Gilmartin	22-Jul-10
20	Ensure all power lines are identified prior to any excavation or piling work	Construction	EPC			

4.5.3 Conclusion of HAZID

Seventeen action items were resolved during FEED. The three remaining items were assigned to the EPC phase, and will be followed up during the EPC phase of the project. These items are show in Table 4.7.

Table 4.7 Remaining HAZID action items (assigned to the EPC phase).

No:	Description:	By:	Due:	Response:	By:	Date:
7	Discussions with authorities need to be opened to discuss impact of capture plant on operating permit, with respect to emissions.	JV Project	EPC			
10	Capture plant and MPP3 operators to be trained regarding emergency response planning.	JV operations	EPC			
20	Ensure all power lines are identified prior to any excavation or piling work.	Construction	EPC			

4.5.4 Material Safety Data Sheets

The Material Safety Data Sheets (MSDS) of sodium hydroxide and mono ethanol amine (MEA) can be found in Annex 1 of Ref 1.

5. FEED and Capture & Compression Costs

5.1 Introduction

This section gives an overview of the costs of the capture and compression system for ROAD, both the project development costs spent prior to project termination, and the estimated capital and operating costs of the proposed plant. Details on the costs must be omitted because they are based on confidential commercial contracts from suppliers. However, an overview is given to give an understanding of the build-up of the costs.

5.2 Project Development Costs

The major costs for project development of ROAD can be broken down into the following work packages and listed as follows:

Description	Cost €k	Approx time period
ROAD Project Engineering team, including • Seconded staff from parents • Specialist procurement support • Travel and other minor costs	1 148	2010-2017
The Capture Plant FEED studies 2010, including • Preparatory work (scoping, design and FEED specification) by parent company specialists • Full FEED studies by two suppliers • Specialist technical support	12 760	2010
Subsequent project development to FID including • Value engineering • Detail engineering • Long lead item contracting • Parent company specialist support • Engineering and project management for MPP3 interfaces • Updates 2014/2015 and remobilization 2017	14 621	2011-2017 (mostly 2011-2012)
MPP3 interfaces external contracts covering: • Engineering, surveys and environmental modelling • Design and construction of the stack tie-ins • Design and construction of the steam tie-ins	3 267	2011-2013
Total	***31 796***	

(A more detailed table of costs against accounting category is shown in the close-out report on Finance and Control, but this more detailed table does not give any descriptions of work scope)

These costs were higher than would normally be expected for engineering costs for a large project prior to FID for three reasons:

1. The tie-ins and the capture plant are both one-off bespoke designs, hence it was necessary to fully engineer (via FEED studies) and procure the major components in order to come to a firm price. ROAD chose to fund two competitive FEED studies to ensure the best value for money. This was successful, in that the difference in capex between suppliers was significantly greater than the costs of the extra FEED study. However, for more standard equipment, this would not be necessary.

2. Due to the original EEPR grant deadline of end 2014, additional detail design and procurement work was carried out in 2011 and early 2012 to allow contruction to finish by that date, including placing seven contracts for long lead items on limited engineering release. This was necessary to maintain the schedule rather than the price.
3. The delays to the project added to the costs. Fluor were asked to provide firm prices for an FID end 2010, end 2011 and June 2012. This resulted in re-work. In addition, there were updates made in 2014, and re-engineering based on the latest technical information and the new transport and storage scope from Dec 2016 to June 2017.

If the project were able to be delivered efficiently on a consistent time schedule, it is likely that perhaps 20% of these costs could have been saved. Some cost planned for 2017-2018 could also be avoided, as some re-engineering was planned to accommodate the scope changes and technology improvements in more detail.

The total capital cost of the capture plant, including interfaces, is estimated at €287.7M, including the above costs. Thus project development prior to FID in this case was 11% of the total capital cost.

5.3 CAPEX estimate of Capture Plant

The original capital cost estmate for capture plant EPC scope was previously reported in 2012 as follows (Non-confidential FEED Study Report, Ref 1):

Capture EPC cost estimate 2012	Cost €M
• Equipment	60-70
• Materials and Labour	65-75
• Engineering	15-20
• Indirect field costs	5-10
• Owners costs (operator training and first fills)	1-2
• Financial and other costs	25-35
Total	***170-210***

This estimate included the capture plant itself, flue-gas ducts to the power plant, compression and all balance of plant and utilities within the capture plant site area. It did not include the steam connections to MPP3, the cooling water ducts outside the capture plant area, nor connections for water (demin water supply, condensate supply and two return lines, storm water, fire water, drinking water and sewage), electrical power or CO_2 export from the site.

In the course of project development from 2012 to 2017, there were a significant number of scope changes, the largest of these being the addition of the WESP, and the reduction in CO_2 compression required at the site. A number of other changes were required to reflect changes at the power plant. A result of this was that that the site layout and detailed engineering needed to be substantially revised with also the associated cost of rework. However, because the re-engineering did not reach the same level of detail in 2017 as achieved in 2012, there was no formal updated EPC price.

Based on the scope changes, ROAD forecast an updated EPC price for 2017 as follows:

Capture EPC cost estimate 2017	Cost €M
- EPC cost estimate 2012	170-210
- Inflation 2012-2017	5-10
- Improved solvent management	2-5
- WESP	10-15
- Saving from reduced compression	– 3-7
Total	***185-230***

The full costs of the capture plant must also include the following costs, which are outside the scope of the EPC contractor (Fluor).

Capture Costs in addition to the EPC cost 2017	Cost €M
- Technology licence fee	
- CO_2 pipeline on the Uniper plot	1-2
- Electrical connection	1-2
- Steam and condensate connections	5-10
- Pipe bridge including civil engineering	2-5
- Cooling water connections	1-2
- Infrastructure costs (roads, fences, construction utilities)	3-5
- Site management	2-3
- Land rental costs	2-4
- Outage compensation for MPP3	1-4
- Power plant staff costs	1-2
- ROAD project engineering costs: engineering, support, management and quality control	10-20
- Sunk costs (not recoverable)	10-25

As noted, full details of the above cost estimates are not given to protect commercial / supplier confidentiality.

The total capital cost of the capture plant, including interfaces and sunk costs, is estimated at €287.7M

5.4 Owner´s Engineering

For the costs spent to date, costs traditionally ascribed to "owner's engineering" are spread across a number of accounting categories in our financial records. ROAD finds it difficult to give a clear value for this because:

- Although the capture plant itself has a traditional EPC approach, the power station was constructed multi-lot with much of the engineering performed in-house by Uniper. The same approach was used for the site connections between the power station and the capture plant.

- Much of the "owner's engineering" was provided by the parent company engineering divisions (for Uniper this is Uniper Technology Group – UTG, for Engie this is Laborelec and Tractebel). As such, they are accounted as sub-contracting, and recorded in the same way as the engineering for the connections above.

Using as a proxy for "owner's engineering" the total costs spent and planned for engineering support staff from the parent companies, we can build up an estimate for "owner's engineering" to date on the capture plant (including MPP3 connections) as follows:

Parent company engineering support costs 2010-2017	Cost €M
• Base and detail engineering	4.2
• FEED study support costs	3.6
• Procurement support	0.2
Total	**8.0**

For future costs, ROAD has the same difficulty – that owner's engineer costs for the power plant connections are included in the cost estimates used for these connections. However, it appears that €15M would be a reasonable estimate for the future costs of owner's engineering, bringing the total to an estimated €23M or 8% of the total capture plant cost.

5.5 Operating costs estimate: variable costs, maintenance, staff costs

The estimates for the operating costs that were developed by ROAD are based on data supplied by Fluor, data from Uniper on the experience of operating and maintaining the Wilhelmshaven pilot, and data from local sources including grid connection charges, cost of the land lease (the Uniper plot is leased from the Port of Rotterdam) and the level of applicable local taxes.

The single biggest costs are the use of electricity and steam by the capture plant. The steam supply from the power plant would result in a loss of generating capacity, and ROAD would compensate the power plant for this as a cost of lost electrical output. Therefore, for the purposes of operating costs estimation, a total electrical consumption can be used which is the sum of the electricity use, and the loss of generating capacity. This was estimated at 58.4 MW, of which just over half is from steam consumption. It should be noted that this figure was not re-adjusted for the updated design developed in 2017. It is quite possible that a small upward revision would be required due to additional compression costs since the new design includes a less efficient air-cooled condenser stage at the Q16-Maas well location. This estimate includes all compression power. It also includes a margin of order 3 MW to allow for some periods with off-design operation, which can result in increased cost of steam because the power plant is at reduced load, or part load operation of the capture plant.

The operating costs of the capture and compression plant is estimated as follows:

	€M/year
Fixed costs	
Operational staff	3.0
Annual maintenance	2.7
Grid charges (Stedin)	1.0
Land rent and taxes	0.6
Variable costs assuming 6500 hours/year = 1.1 Mt/year CO_2 stored	
Chemicals (€0.7/t)	0.8
Electricity and steam @ €55/MWh	20.9

TOTAL	29.0

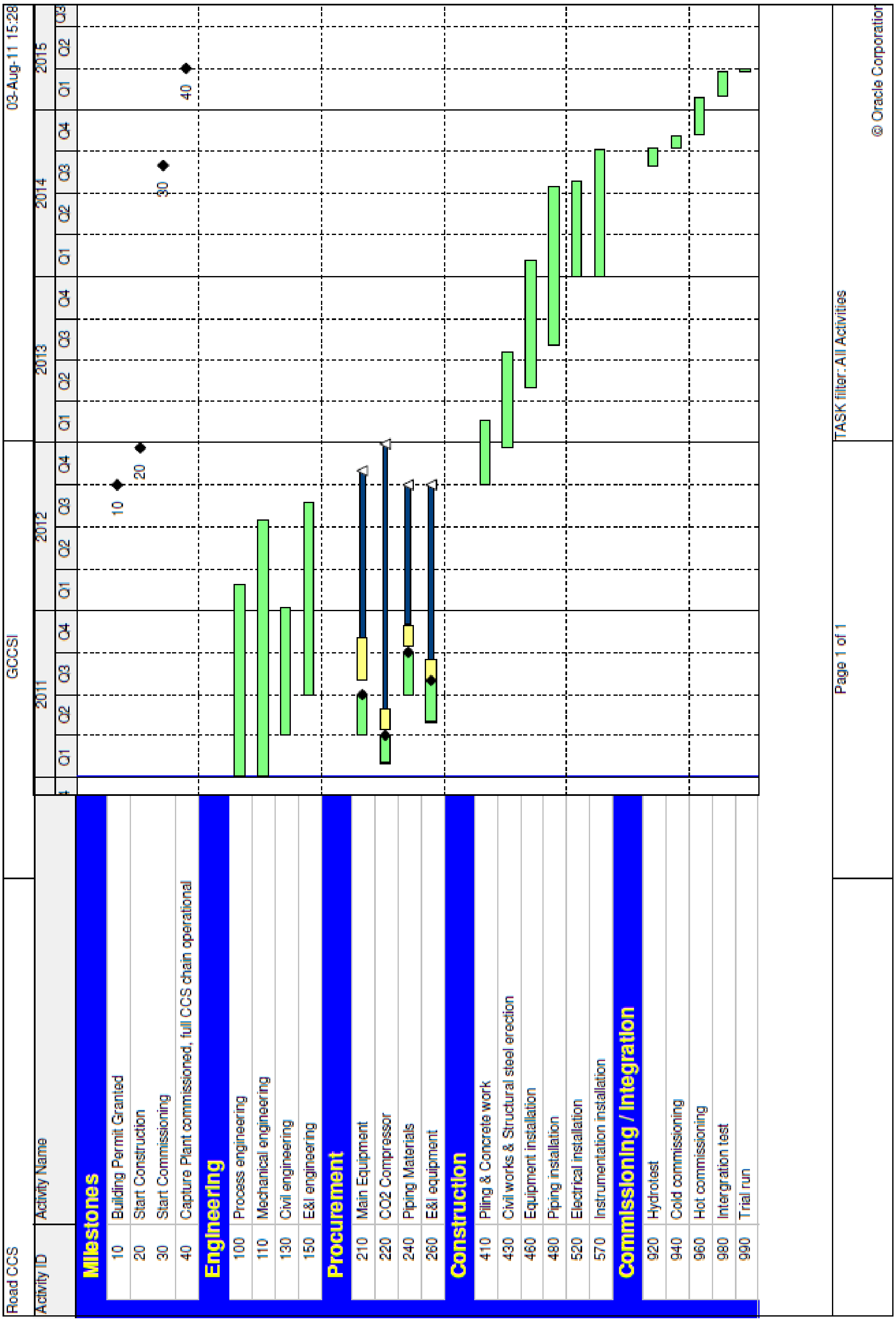
Clearly the operating costs are dominated by the cost of electricity and steam, and this in turn depends on the energy penalty of the capture plant, the local cost of electricity, and the costs of supplying steam to the capture plant. In fact the cost of electricity has averaged well below €55/MWh for the past few years in the Netherlands, and it is expected to remain depressed due to growing supply from renewable sources. Therefore, had the project been built, the actual operating cost is likely to have been lower than the estimated cost shown above.

5.6 Project Planning and Construction Programme

The construction programme had not been updated at the point when the project was halted in 2017. Therefore the only schedule that was worked out in detail was the one being followed in 2011 and early 2012 designed to ensure that construction would be complete by end of 2014 (the deadline in the EEPR grant at the time). This schedule was presented at high level in the non-confidential FEED study report (Ref 1), and the Gantt chart is reproduced here for ease of reference as Figure 5.1.

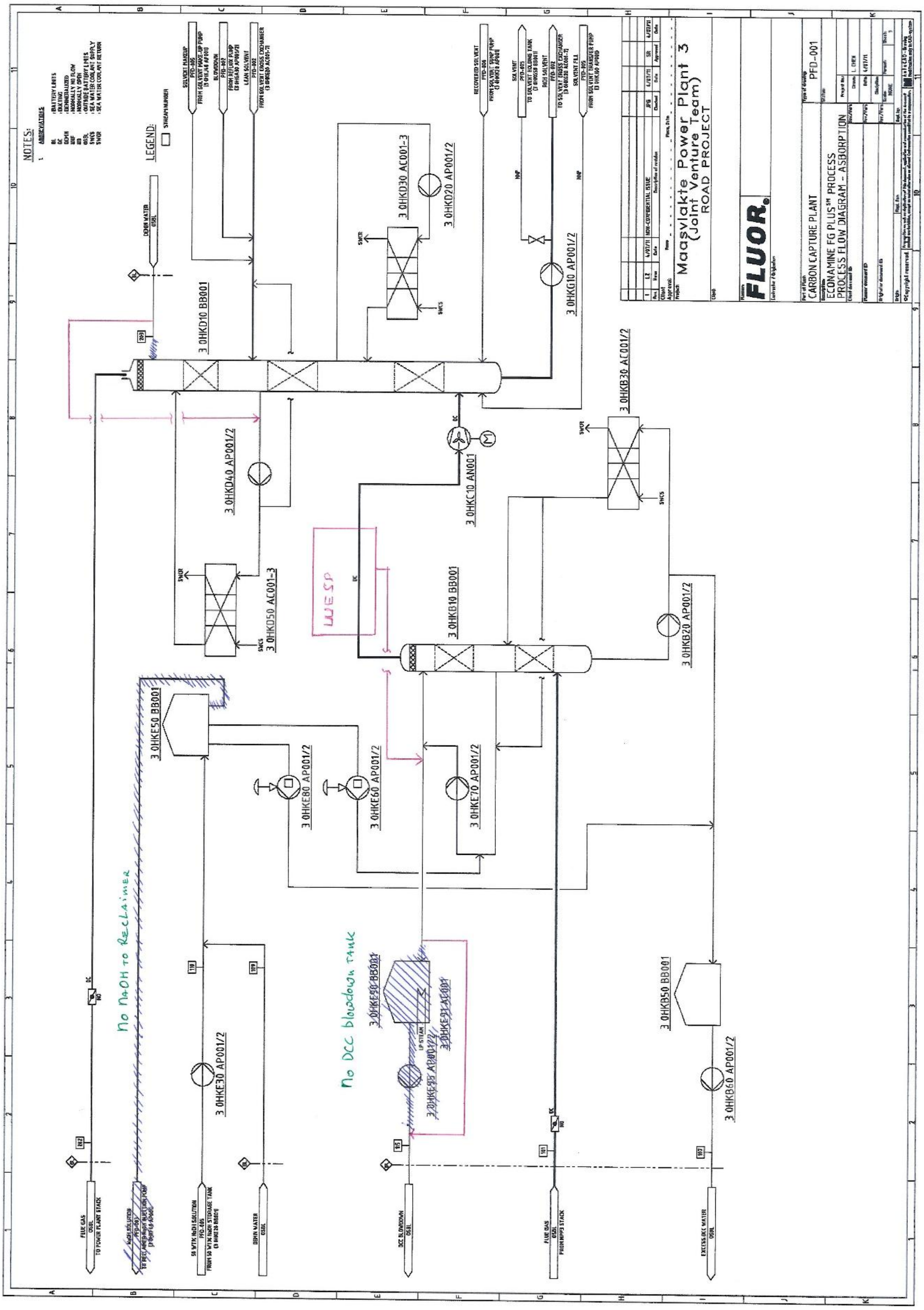
The FID is not shown on the schedule as an explicit milestone. This schedule was developed with the intent of FID taking place before the end of 2011. Obviously, the later the FID, the greater the proportion of costs committed before FID. This schedule was followed until the end of Q1 2012, shortly before the project was suspended and “slow-mode” introduced.

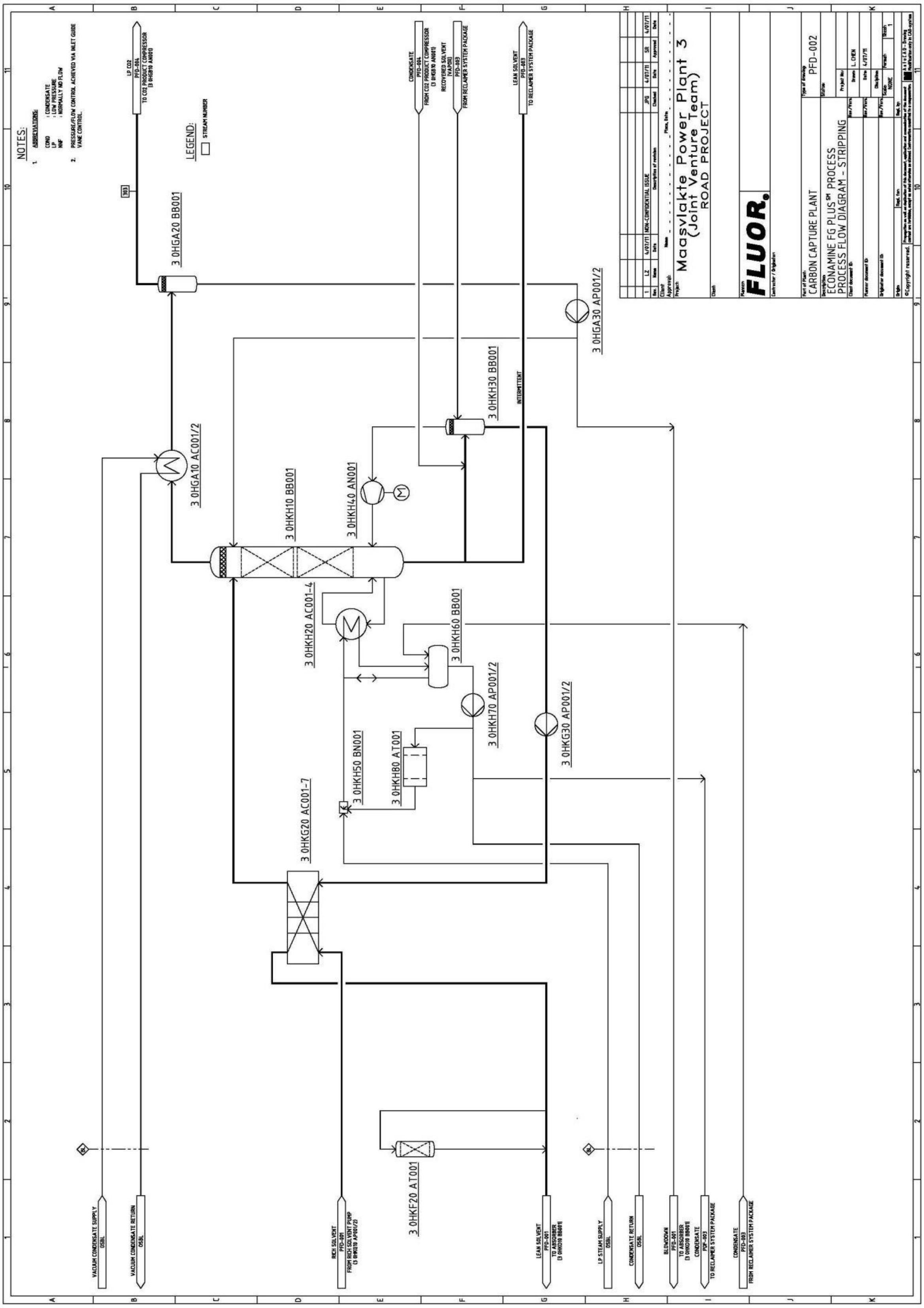
Figure 5.1 Construction schedule for the capture plant 2011 & Q1 2012



6. Annexes

6.1 Simplified Process Flow Diagrams (PFDs)




NOTES:
1. ABBREVIATIONS:
COND : CONDENSATE
LP : LOW PRESSURE
NNF : NORMALLY NO FLOW
2. PRESSURE/FLOW CONTROL ACHIEVED VIA INLET GUIDE VANE CONTROL.
LEGEND:
STREAM NUMBER
303
LP CO2
PFD-004
TO CO2 PRODUCT COMPRESSOR
(3 0HGB10 AN001)
VACUUM CONDENSATE SUPPLY
OSBL
VACUUM CONDENSATE RETURN
OSBL
BL
RICH SOLVENT
PFD-001
FROM RICH SOLVENT PUMP
(3 0HKG10 AP001/2)
LEAN SOLVENT
PFD-001
TO ABSORBER
(3 0HKD10 BB001)
LP STEAM SUPPLY
OSBL
CONDENSATE RETURN
OSBL
BLOWDOWN
PFD-001
TO ABSORBER
(3 0HKD10 BB001)
CONDENSATE
PDF-003
TO RECLAIMER SYSTEM PACKAGE
CONDENSATE
PFD-003
FROM RECLAIMER SYSTEM PACKAGE
CONDENSATE
PFD-004
FROM CO2 PRODUCT COMPRESSOR
(3 0HGB10 AN001)
RECOVERED SOLVENT
(VAPOR)
PFD-003
FROM RECLAIMER SYSTEM PACKAGE
LEAN SOLVENT
PFD-003
TO RECLAIMER SYSTEM PACKAGE
INTERMITTENT
3 0HGA10 AC001/2
3 0HGA20 BB001
3 0HKH10 BB001
3 0HKG20 AC001-7
3 0HKH20 AC001-4
3 0HKH40 AN001
M
3 0HKH50 BN001
3 0HKH80 AT001
3 0HKH60 BB001
3 0HKH70 AP001/2
3 0HKH30 BB001
3 0HKF20 AT001
3 0HKG30 AP001/2
3 0HGA30 AP001/2
1 LZ 4/07/11 NON-CONFIDENTIAL ISSUE JPG 4/07/11 SR 4/07/11
Rev. Name Date Description of revision Checked Date Approved Date
Client Approval: Name Place, Date
Project: Maasvlakte Power Plant 3
(Joint Venture Team)
ROAD PROJECT
Client:
Planner: FLUOR
Contractor / Originator:
Part of Plant: CARBON CAPTURE PLANT
Type of drawing: PFD-002
Description: ECONAMINE FG PLUS℠ PROCESS
PROCESS FLOW DIAGRAM - STRIPPING
Status:
Client document ID:
Planner document ID:
Originator document ID:
Rev./Vers.
Project No:
Drawn: L. CHEN
Date: 4/07/11
Discipline:
Scale: NONE
Format:
Sheet: 1
Origin:
Repl. for:
Repl. by:
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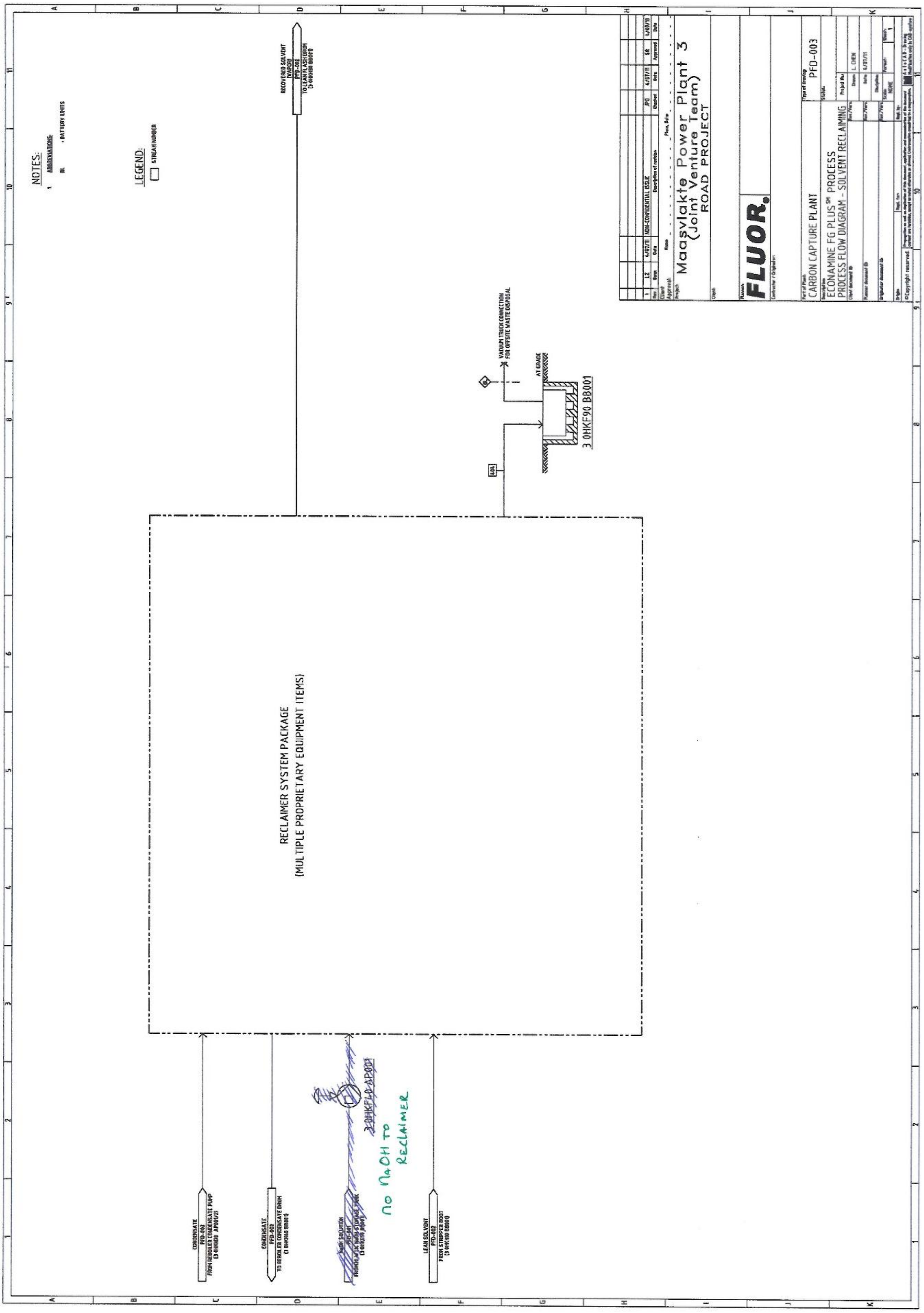
NOTES:
1 ABBREVIATIONS:
BL : BATTERY LIMITS
LEGEND:
☐ STREAM NUMBER
RECOVERED SOLVENT (VAPOR)
PFD-002
TO LEAN FLASH DRUM (3 0HKF30 BB001)
VACUUM TRUCK CONNECTION FOR OFFSITE WASTE DISPOSAL
AT GRADE
3 0HKF90 BB001
RECLAIMER SYSTEM PACKAGE (MULTIPLE PROPRIETARY EQUIPMENT ITEMS)
CONDENSATE
PFD-002
FROM REBOILER CONDENSATE PUMP (3 0HKF20 AP001/2)
CONDENSATE
PFD-002
TO REBOILER CONDENSATE DRUM (3 0HKF40 BB001)
~~NaOH SOLUTION~~
~~PFD-041~~
~~FROM 20 WT.% NaOH STORAGE TANK (3 0HKG30 BB001)~~
~~3 0HKF40 AP001~~
no NaOH to Reclaimer
LEAN SOLVENT
PFD-002
FROM STRIPPER BOOT (3 0HKF10 BB001)
1 | LZ | 4/07/11 | NON-CONFIDENTIAL ISSUE | JPD | 4/07/11 | SR | 4/07/11
Rev. | Name | Date | Description of revision | Checked | Date | Approved | Date
Client Approval: Name Place, Date
Project: Maasvlakte Power Plant 3 (Joint Venture Team) ROAD PROJECT
Client
Planner
FLUOR.
Contractor / Originator
Part of Plant: CARBON CAPTURE PLANT
Type of drawing: PFD-003
Description: ECONAMINE FG PLUS℠ PROCESS PROCESS FLOW DIAGRAM - SOLVENT RECLAIMING
Status
Client document ID
Planner document ID
Originator document ID
Project No
Drawn: L. CHEN
Date: 6/07/11
Discipline
Scale: NONE
Format
Sheet: 1
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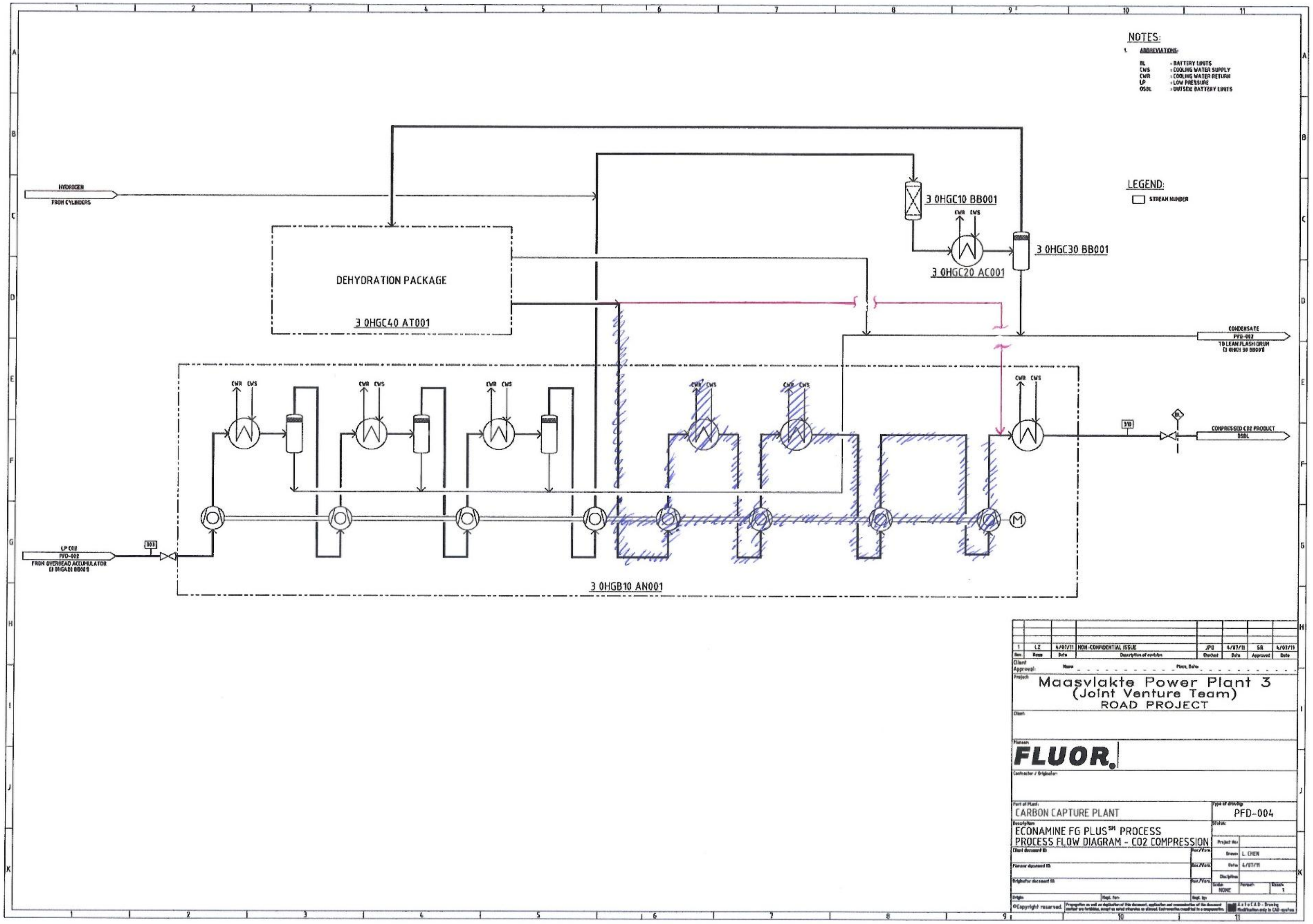
A u t o C A D - Drawing


NOTES:
1. ABBREVIATIONS:
BL : BATTERY LIMITS
CWS : COOLING WATER SUPPLY
CWR : COOLING WATER RETURN
LP : LOW PRESSURE
OSBL : OUTSIDE BATTERY LIMITS
LEGEND:
☐ STREAM NUMBER
HYDROGEN
FROM CYLINDERS
LP CO2
PFD-002
FROM OVERHEAD ACCUMULATOR
(3 0HGA20 BB001)
303
DEHYDRATION PACKAGE
3 0HGC40 AT001
3 0HGC10 BB001
3 0HGC20 AC001
3 0HGC30 BB001
CWR CWS
M
3 0HGB10 AN001
CONDENSATE
PFD-002
TO LEAN FLASH DRUM
(3 0HCH 30 BB001)
310
BL
COMPRESSED CO2 PRODUCT
OSBL
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Rev. Name Date Description of revision Checked Date Approved Date
Client Approval: Name Place, Date
Project
Maasvlakte Power Plant 3
(Joint Venture Team)
ROAD PROJECT
Client
Planner
FLUOR
Contractor / Originator
Part of Plant:
CARBON CAPTURE PLANT
Type of drawing
PFD-004
Description
ECONAMINE FG PLUS℠ PROCESS
PROCESS FLOW DIAGRAM - CO2 COMPRESSION
Status
Client document ID
Planner document ID
Originator document ID
Rev./Vers.
Project No.
Drawn L. CHEN
Date 4/07/11
Discipline
Scale NONE
Format
Sheet 1
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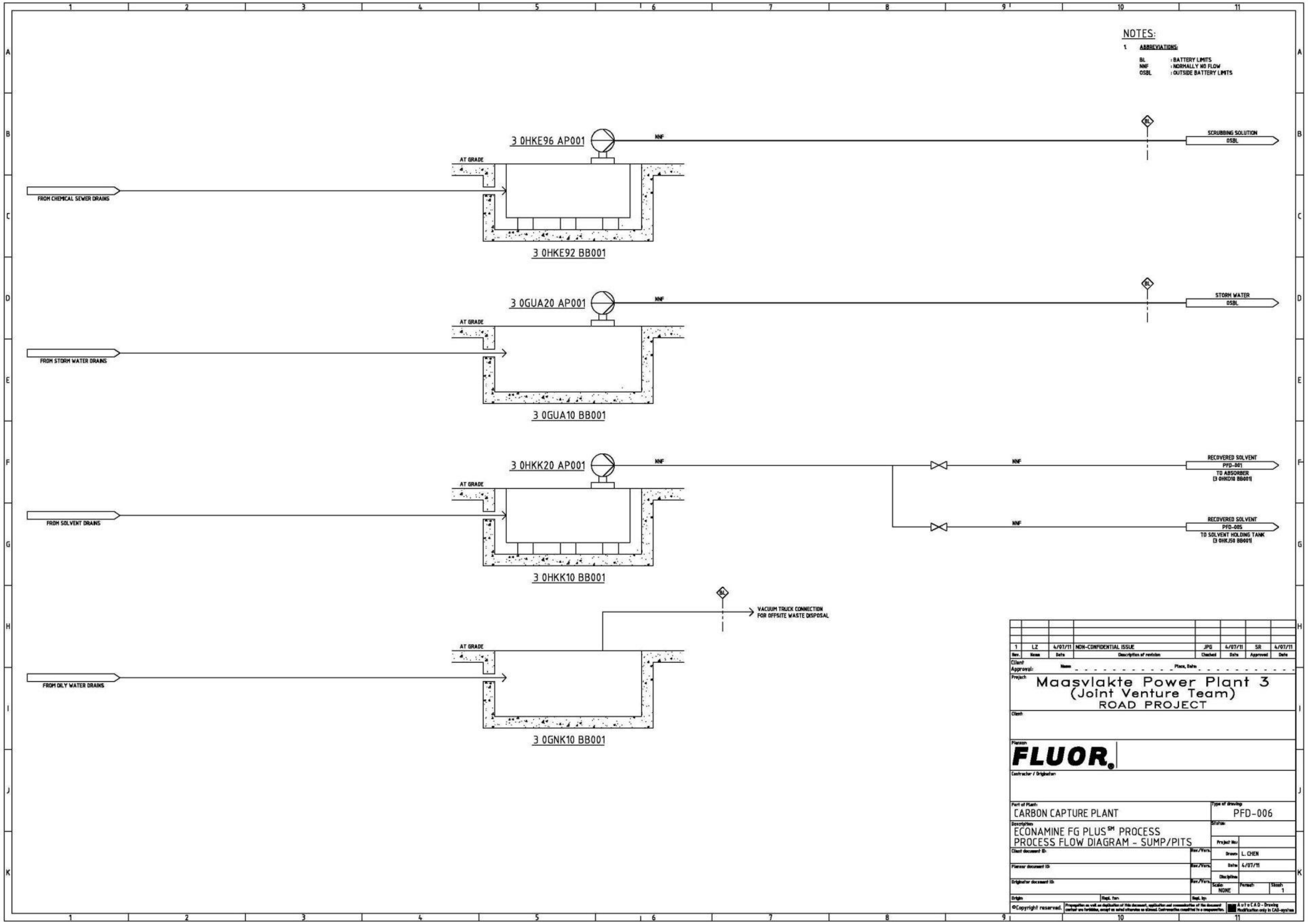
NOTES:
1 ABBREVIATIONS:
BL : BATTERY LIMITS
NNF : NORMALLY NO FLOW
OSBL : OUTSIDE BATTERY LIMITS
3 0HKE96 AP001
NNF
BL
SCRUBBING SOLUTION
OSBL
AT GRADE
FROM CHEMICAL SEWER DRAINS
3 0HKE92 BB001
3 0GUA20 AP001
NNF
BL
STORM WATER
OSBL
AT GRADE
FROM STORM WATER DRAINS
3 0GUA10 BB001
3 0HKK20 AP001
NNF
NNF
RECOVERED SOLVENT
PFD-001
TO ABSORBER
[3 0HKD10 BB001]
NNF
RECOVERED SOLVENT
PFD-005
TO SOLVENT HOLDING TANK
[3 0HKJ50 BB001]
AT GRADE
FROM SOLVENT DRAINS
3 0HKK10 BB001
BL
VACUUM TRUCK CONNECTION
FOR OFFSITE WASTE DISPOSAL
AT GRADE
FROM OILY WATER DRAINS
3 0GNK10 BB001
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NON-CONFIDENTIAL ISSUE
JPG
4/07/11
SR
4/07/11
Rev.
Name
Date
Description of revision
Checked
Date
Approved
Date
Client Approval:
Name
Place, Date
Project:
Maasvlakte Power Plant 3
(Joint Venture Team)
ROAD PROJECT
Client:
Planner:
FLUOR
Contractor / Originator:
Part of Plant:
CARBON CAPTURE PLANT
Type of drawing:
PFD-006
Description:
ECONAMINE FG PLUS℠ PROCESS
PROCESS FLOW DIAGRAM - SUMP/PITS
Status:
Project No:
Client document ID:
Rev./Vers.
Drawn: L. CHEN
Planner document ID:
Rev./Vers.
Date: 4/07/11
Discipline:
Originator document ID:
Rev./Vers.
Scale: NONE
Format:
Sheet: 1
Origin:
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Repl. by:
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AutoCAD - Drawing
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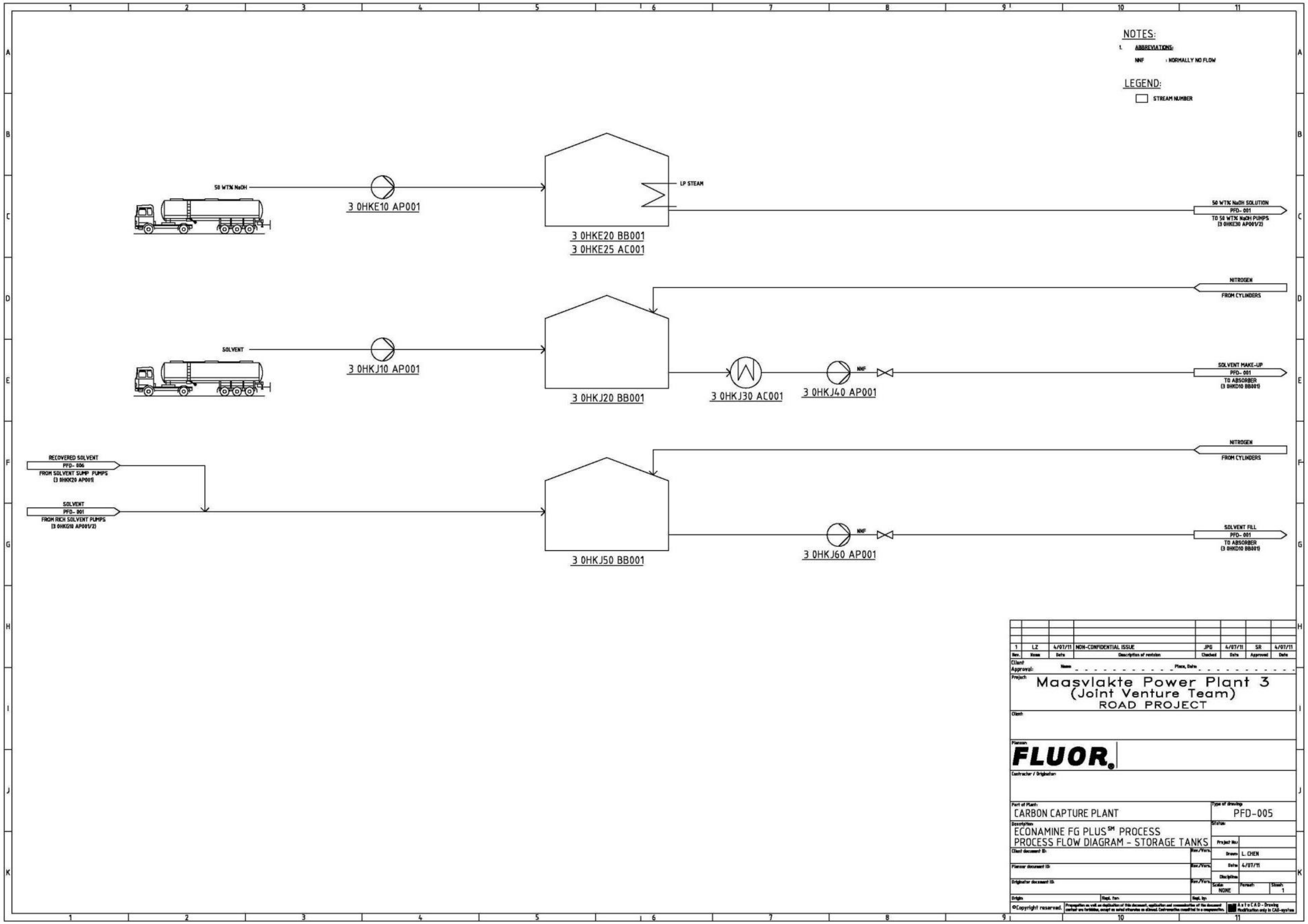
NOTES:
1. ABBREVIATIONS:
NNF : NORMALLY NO FLOW
LEGEND:
☐ STREAM NUMBER
50 WT% NaOH
3 0HKE10 AP001
LP STEAM
3 0HKE20 BB001
3 0HKE25 AC001
50 WT% NaOH SOLUTION
PFD- 001
TO 50 WT% NaOH PUMPS
(3 0HKE30 AP001/2)
NITROGEN
FROM CYLINDERS
SOLVENT
3 0HKJ10 AP001
3 0HKJ20 BB001
3 0HKJ30 AC001
3 0HKJ40 AP001
NNF
SOLVENT MAKE-UP
PFD- 001
TO ABSORBER
(3 0HKD10 BB001)
NITROGEN
FROM CYLINDERS
RECOVERED SOLVENT
PFD- 006
FROM SOLVENT SUMP PUMPS
(3 0HKK20 AP001)
SOLVENT
PFD- 001
FROM RICH SOLVENT PUMPS
(3 0HKG10 AP001/2)
3 0HKJ50 BB001
3 0HKJ60 AP001
NNF
SOLVENT FILL
PFD- 001
TO ABSORBER
(3 0HKD10 BB001)
1 LZ 4/07/11 NON-CONFIDENTIAL ISSUE JPG 4/07/11 SR 4/07/11
Rev. Name Date Description of revision Checked Date Approved Date
Client Approval: Name Place, Date
Project: Maasvlakte Power Plant 3
(Joint Venture Team)
ROAD PROJECT
Client:
Planner:
FLUOR
Contractor / Originator
Part of Plant: CARBON CAPTURE PLANT
Type of drawing: PFD-005
Description: ECONAMINE FG PLUS℠ PROCESS
PROCESS FLOW DIAGRAM - STORAGE TANKS
Status:
Project No:
Client document ID: Rev./Vers.
Drawn: L. CHEN
Planner document ID: Rev./Vers.
Date: 4/07/11
Discipline:
Originator document ID: Rev./Vers.
Scale: NONE
Format:
Sheet: 1
Origin
Repl. for:
Repl. by:
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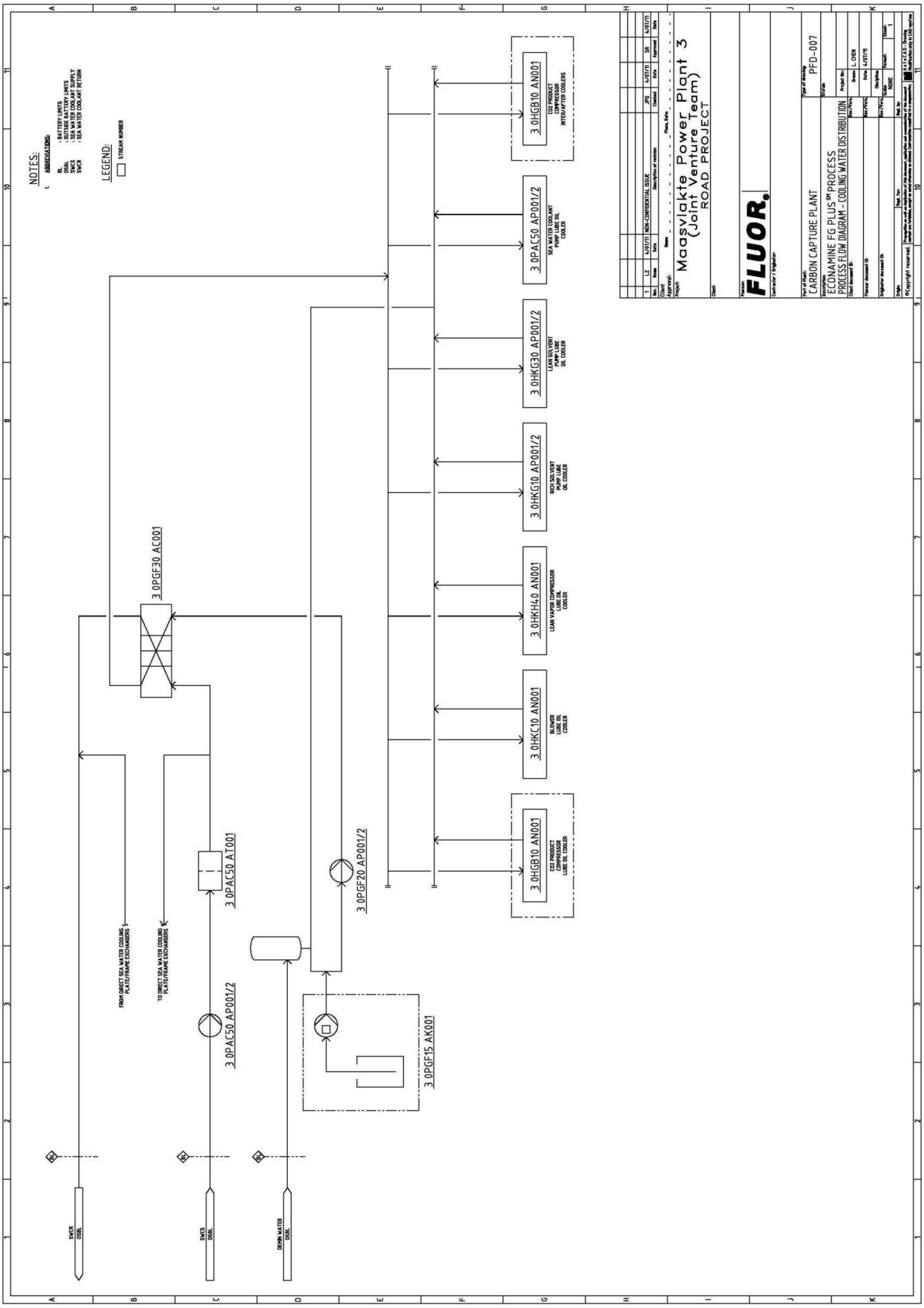
NOTES:
1. ABBREVIATIONS:
BL : BATTERY LIMITS
OSBL : OUTSIDE BATTERY LIMITS
SWCS : SEA WATER COOLANT SUPPLY
SWCR : SEA WATER COOLANT RETURN
LEGEND:
☐ STREAM NUMBER
3 0HGB10 AN001
CO2 PRODUCT COMPRESSOR INTER/AFTER COOLERS
3 0PAC50 AP001/2
SEA WATER COOLANT PUMP LUBE OIL COOLER
3 0HKG30 AP001/2
LEAN SOLVENT PUMP LUBE OIL COOLER
3 0HKG10 AP001/2
RICH SOLVENT PUMP LUBE OIL COOLER
3 0HKH40 AN001
LEAN VAPOR COMPRESSOR LUBE OIL COOLER
3 0HKC10 AN001
BLOWER LUBE OIL COOLER
3 0HGB10 AN001
CO2 PRODUCT COMPRESSOR LUBE OIL COOLER
3 0PGF30 AC001
3 0PAC50 AT001
3 0PGF20 AP001/2
3 0PAC50 AP001/2
3 0PGF15 AK001
FROM DIRECT SEA WATER COOLING PLATE/FRAME EXCHANGERS
TO DIRECT SEA WATER COOLING PLATE/FRAME EXCHANGERS
BL
BL
BL
SWCR OSBL
SWCS OSBL
DEMIN WATER OSBL
A
B
C
D
E
F
G
H
I
J
K
1
2
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NON-CONFIDENTIAL ISSUE
JPG
4/07/11
SR
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Rev.
Name
Date
Description of revision
Checked
Date
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Date
Client Approval:
Name
Place, Date
Project:
Maasvlakte Power Plant 3
(Joint Venture Team)
ROAD PROJECT
Client:
Planner:
FLUOR
Contractor / Originator:
Type of drawing:
PFD-007
Status:
Part of Plant:
CARBON CAPTURE PLANT
Description:
ECONAMINE FG PLUS SM PROCESS
PROCESS FLOW DIAGRAM - COOLING WATER DISTRIBUTION
Client document ID:
Planner document ID:
Originator document ID:
Origin:
Repl. for:
Repl. by:
Rev./Vers.
Rev./Vers.
Rev./Vers.
Project No:
Drawn:
L. CHEN
Date:
4/07/11
Discipline:
Scale:
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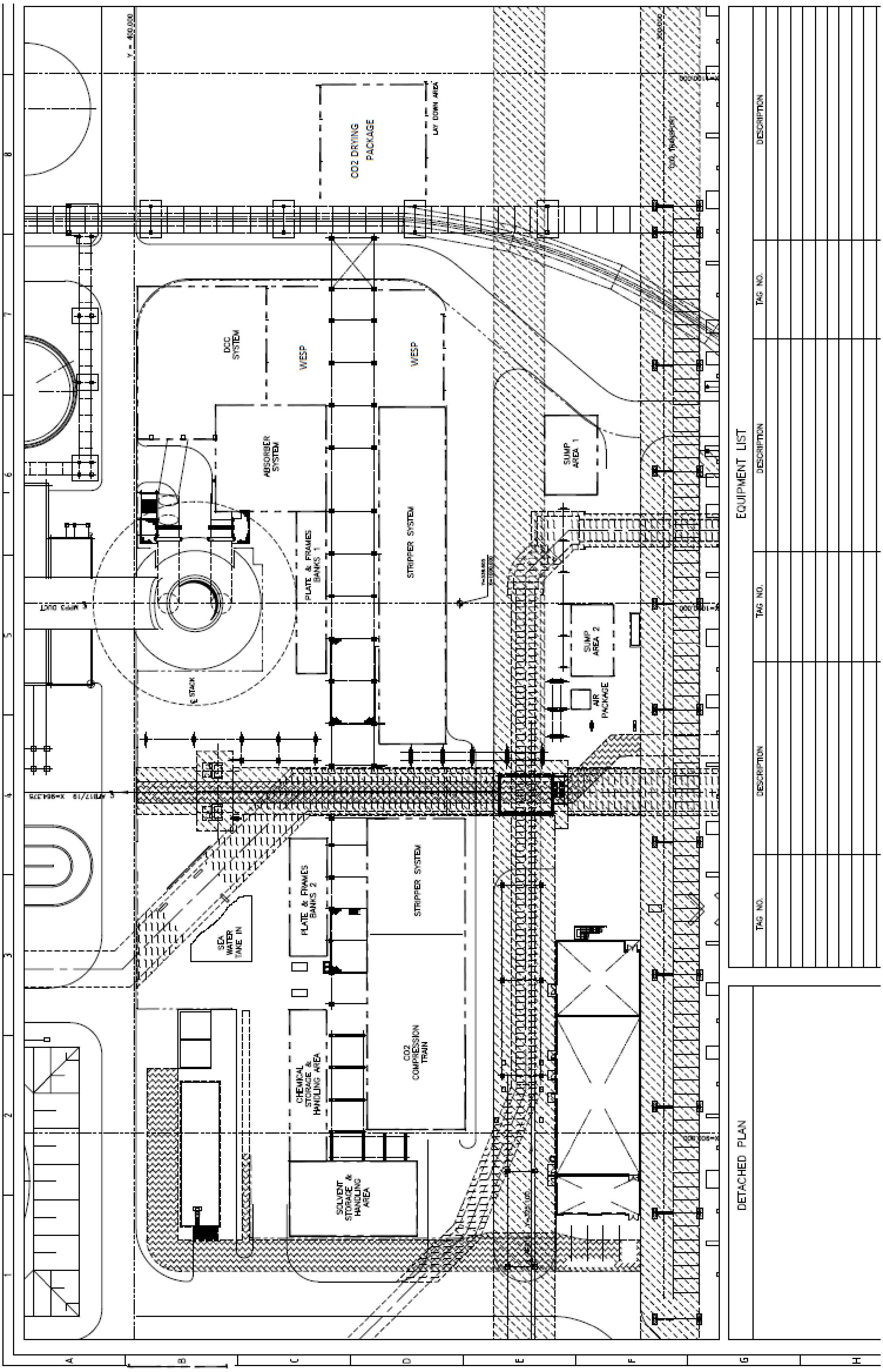
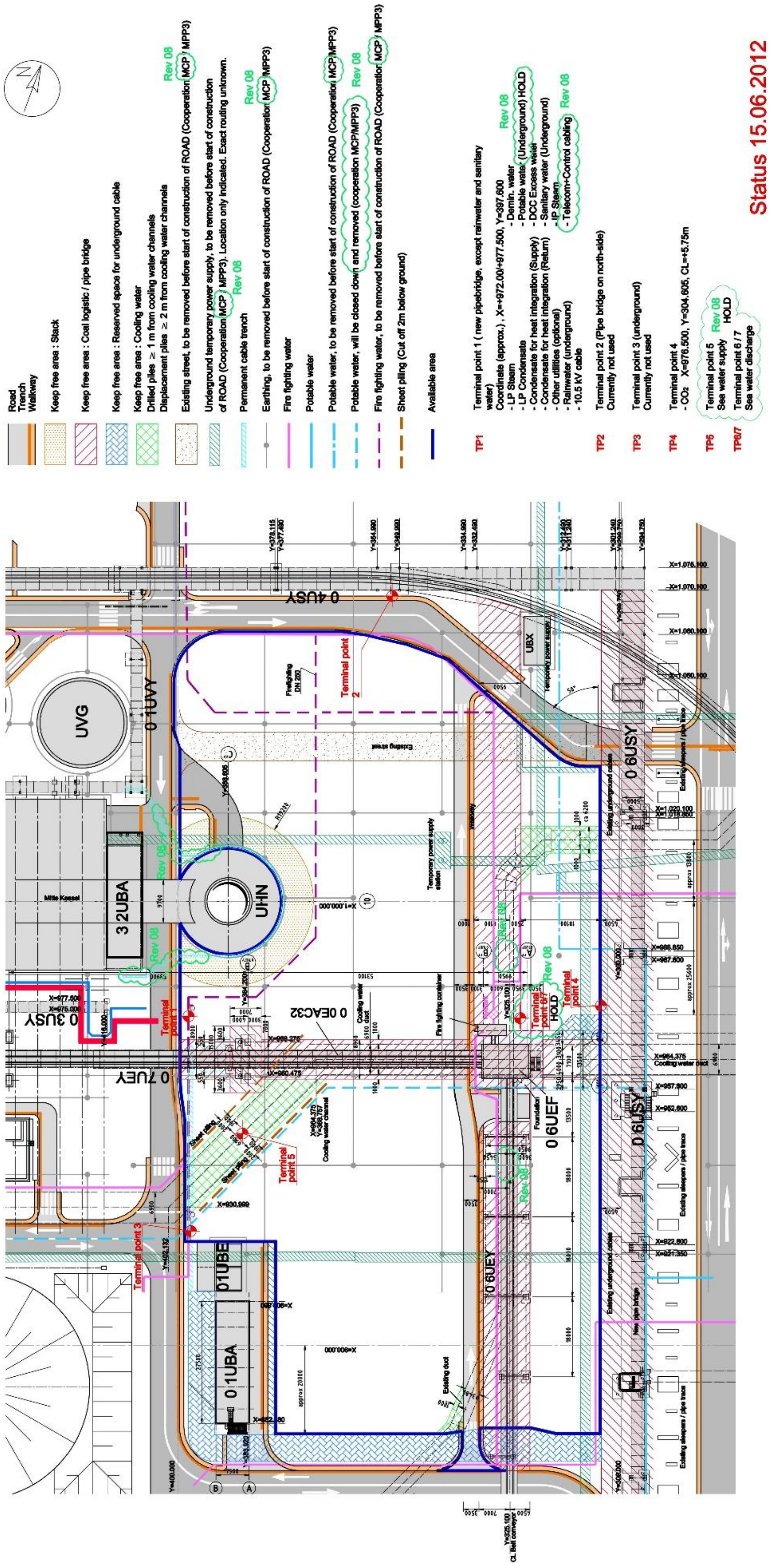
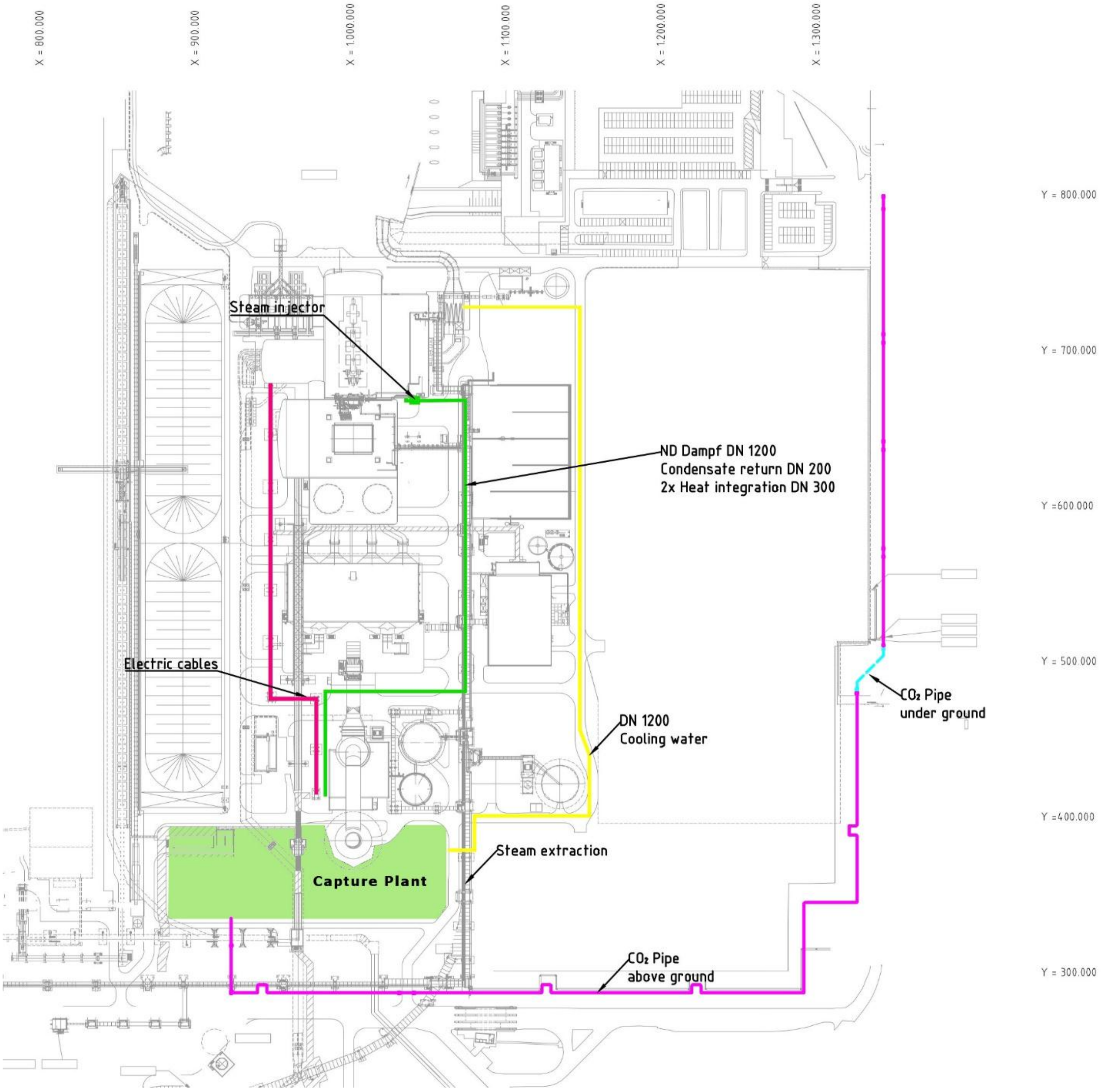
6.2 Simplified Plot Plan



6.3 Keep Free Area and Transfer Points

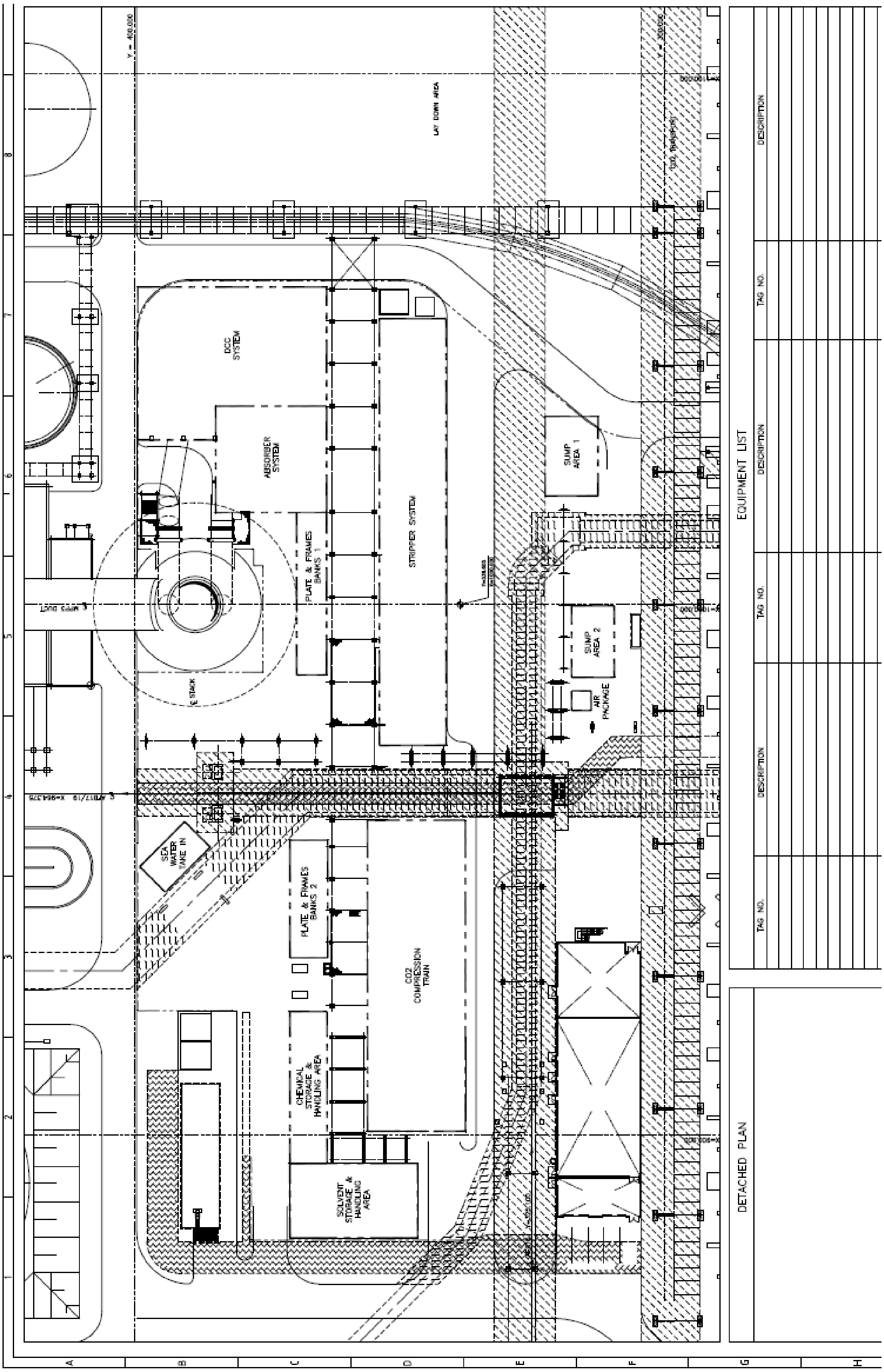


6.4 On-site Pipeline Routes

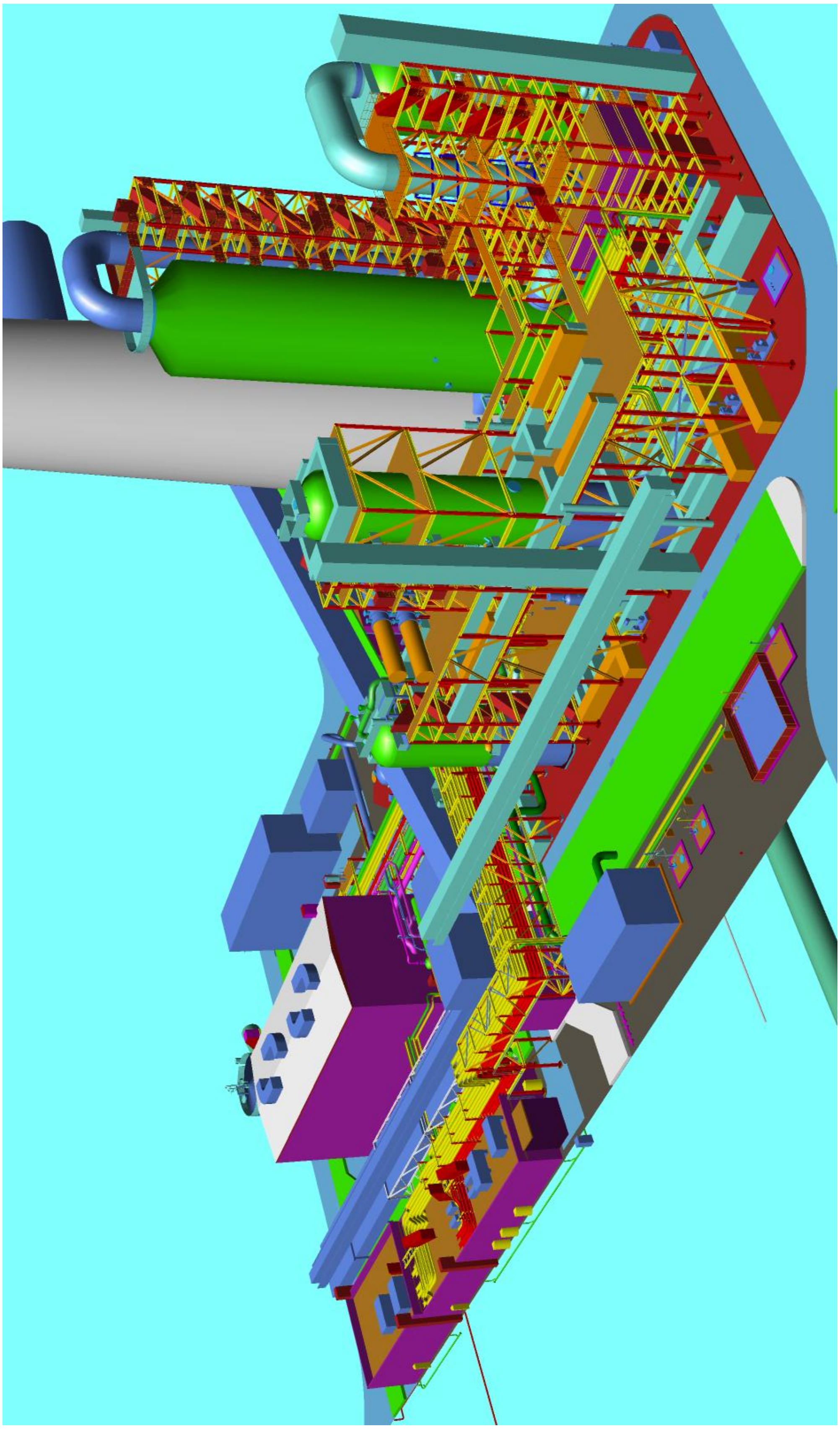


6.5 Original General Arrangement (from 2012)

Simplified Layout of the design in 2012



3D view of the capture plant (2012)



6.6 Attached References

1. Non-confidential FEED study report, Special report for the GCCSI, November 2011
2. CO_2 capture technology selection methodology, Special report for the GCCSI, August 2011
3. Reduction of freshwater usage of a coal fired power station with CCS be applying a high level of integration of all water streams, by Hylkema and Read, for the GHGT-12 conference, 2013.
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7. A wet electrostatic precipitator (WESP) as countermeasure to mistformation in amine based carbon capture, by Mertens, Anderlohr, Rogiers, Brachert, Khakharia, Goetheer, and Schaber International Journal of Greenhouse Gas Control, October 2014
8. Integration of the 250 MWe demo post-combustion CO_2 capture plant at MPP3, by Magneschi, Hylkema and Stienstra for the POWER-GEN Europe conference, 12-14 June 2012, Cologne
9. Environmental Impact Assessment for the ROAD Project permitting submitted 2011 (in Dutch).