Foreword

This Key Knowledge Reference Book is the result of a Front End Engineering and Design (FEED) study undertaken by E.ON following the award of a FEED contract with the Department of Energy and Climate Change (DECC) in March 2010.

This FEED was delivered by a dedicated team of around 110 experts. These experts comprised many different disciplines from Mechanical, Civil and Electrical engineers to Geologists and Ecologists and also included Lawyers, Accountants, Surveyors and many other professionals. The FEED brought together and integrated expertise from several distinct industries: process plant, power plant and offshore oil and gas, from a total of 17 different organisations. Finally, the FEED team included expertise from as far afield as Japan, Germany and Aberdeen as well as significant expertise from E.ON New Build & Technology based in Nottingham and Gelsenkirchen and Hannover in Germany. Despite these challenges, this FEED was delivered in a substantive period of only 9 months and for significantly less than budget.

The Key Knowledge Reference Book is publicly available to all CCS project developers and other interested parties to ensure the lessons learned from this FEED are disseminated as widely as possible to advance the roll-out of Carbon Capture and Storage. We hope you find this Key Knowledge Reference Book useful. If there are any queries or questions please contact us on kingsnorthenquiries@eon-uk.com.

I would like to express my thanks to the dedication to everyone involved in this FEED process, including the invaluable guidance and assistance provided by DECC during this process.

Regards

Stephen Beck
General Project Manager – Kingsnorth & CCS
1. Executive Summary

1.1 Project Outline

E.ON is one of the UK’s leading energy companies – generating and distributing electricity, and retailing power and gas to around 5.5 million homes and businesses. It is part of the E.ON group, one of the world’s largest investor-owned power and gas companies. It employs around 16,000 people in the UK and more than 92,000 people worldwide. E.ON is one of the largest operators and developers of power stations in the UK using some of the most advanced technologies available.

During 2010-11, as part of the Carbon Capture & Storage (CCS) Demonstration Competition process, E.ON undertook a preliminary Front End Engineering Design (FEED) study for the development of a commercial scale CCS demonstration plant on the planned supercritical coal fired power station at Kingsnorth in Kent, South East England.

The Kingsnorth CCS Project consists of two 800MW power generating units at Kingsnorth power station, a 300MW (net) post combustion carbon capture plant integrated into the power plant with associated dehydration and compression facilities, a 36” pipeline for transportation of CO2 to the Hewett gas field in the southern North Sea and a new platform at this field with associated injection facilities and wells.

1.2 Kingsnorth CCS FEED Study

The Kingsnorth CCS Front End Engineering and Design (“FEED) study was designed to advance the technical, commercial, permitting and regulatory understanding with regards to the design and implementation of CCS at Kingsnorth. Furthermore, this FEED study was designed to de-risk the further development of the project by providing sufficient design specification and clarity on consenting and permitting requirements and enabling more detailed costing information to be sourced. As such, the FEED study played an important role in the early development of the project, giving a preliminary but reliable indication of the commercial viability of the project.

However, the activities included in the FEED study also reflect changes in the energy market environment caused by the global credit crisis and recession. The associated reduction in energy demand has led to a short-term overcapacity in the electricity
generation market in the UK. The impact of this was to cause a delay in the
timescales within which Kingsnorth CCS could proceed and moved the timescales
outside those envisaged by the CCS Demonstration Competition. In consequence,
in October 2010, E.ON announced that it would be unable to proceed with
Kingsnorth within this competition process. As part of this announcement process,
E.ON discussed with DECC how to ensure maximum value for money would be
obtained from the FEED process. As a result the work programme for the FEED
was optimised to ensure the maximum benefit would be obtained from knowledge
transfer.

In the meantime, various consultations in relation to the energy market have
continued: their conclusions will take time to filter into legislation on new market
support mechanisms for lower carbon generation, creating short term uncertainty
over the long-term viability of new generation investment.

Therefore, a multi-stage project development plan was developed to align with
anticipated changes in the energy market and electricity demand as well as
delivering the requirements of the UK Government Competition. As part of this multi-
stage process, the FEED study was designed to continue the effective development
of the project and deliver price certainty within the fixed period of time set out under
the UK Government CCS Demonstration Competition. As such, the current activities
undertaken and shared within this Key Knowledge Reference Book cover only the
early stages of a full FEED study, building on other development activities and
feasibility studies which had taken place in the months preceding the UK
Government Competition.

The stages of the project development plan are illustrated in the chart below and are:

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<td>FEED Phase #1</td>
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<td>Submit ISDS</td>
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In summary, the development stages for the Kingsnorth CCS project are as follows:

- **Feasibility or Pre-FEED** – Concluded at the start of 2010, feasibility and Pre-FEED works focussed on testing the feasibility of the proposed engineering at Kingsnorth CCS and set over-arching design philosophies;

- **FEED Phase #1A** – Undertaken under the UK Government CCS Demonstration Competition. FEED Phase #1A focussed on the long lead consenting process for the CO2 pipeline and the main power and carbon capture plant, licensing and safety cases, integrated plant and process cycle design, CCS chain and power plant integration, site layout and CCS chain costs;

- **FEED Phase #2** – The focus shifts towards engineering and the continuation of consenting processes. The engineering design of the CCS chain from capture plant to transport and storage continues with specification for major components. A procurement exercise in relation to the major cost items for the main plant and carbon capture, transport and storage chain elements will be undertaken to finalise design and obtain a greater degree of price certainty.

The Kingsnorth CCS FEED study has significantly advanced the technical, commercial and regulatory understanding with regards to the design and implementation of CCS. As part of the FEED process, E.ON agreed to transfer this knowledge to the wider CCS community, including developers, investors, consenting authorities, regulators, nation states as well as industrial, environmental and public stakeholders. E.ON is fully supportive of this Knowledge Transfer process and is therefore making available a significant quantity of the FEED study and other information, in the form of this Key Knowledge Reference Book.
1.3 The Key Knowledge Reference Book

This Key Knowledge Reference Book comprises information provided in the following structure:

- Project Design
- Technical Design – Carbon Capture and Compression Plant
- Technical Design – Pipeline and Platform
- Technical Design – Wells and Storage
- Health and Safety
- Environment and Consents
- Project Management Reports

Further commentary on each of the sections is provided to give both context to the information supplied and to pull out key areas of learning in each section.

It should be noted that whilst the Kingsnorth CCS FEED study encompasses a range of technical and commercial works, information which is deemed to be commercially confidential is excluded from this Key Knowledge Reference Book. This includes information belonging to E.ON’s key technology suppliers, the disclosure of which would allow re-engineering of underlying intellectual property, or would contravene E.ON’s confidentiality obligations. Such information is therefore ‘black-listed’ and excluded from this Key Knowledge Reference Book.
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<td>AGI</td>
<td>Above Ground Installation on an otherwise buried pipeline</td>
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<td>ALARP</td>
<td>As Low As is Reasonably Practicable (term applied to risk)</td>
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<td>American Petroleum Institute</td>
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<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IP</td>
<td>Intermediate Pressure</td>
</tr>
<tr>
<td>JT or J/T</td>
<td>Joule-Thomson change in gas temperature due to expansion or compression</td>
</tr>
<tr>
<td>LCPD</td>
<td>Large Combustion Plant Directive</td>
</tr>
<tr>
<td>LP</td>
<td>Low Pressure</td>
</tr>
<tr>
<td>MAH</td>
<td>Major Accident Hazard</td>
</tr>
<tr>
<td>MAPD</td>
<td>Major Accident Prevention Document</td>
</tr>
<tr>
<td>MCR</td>
<td>Maximum Continuous Rating (of a power plant in MW)</td>
</tr>
<tr>
<td>MSDS</td>
<td>Material Safety Data Sheet</td>
</tr>
<tr>
<td>MSG</td>
<td>Minimum Stable Generation (of a power plant in MW)</td>
</tr>
<tr>
<td>NFPA</td>
<td>National Fire Protection Association (USA)</td>
</tr>
<tr>
<td>NOX</td>
<td>Nitrogen Oxides</td>
</tr>
<tr>
<td>NUI</td>
<td>Normally Unmanned Installation</td>
</tr>
<tr>
<td>OPAPP</td>
<td>Operating Philosophy of Abated Power Plant (Working Group)</td>
</tr>
<tr>
<td>OSWG</td>
<td>Operational Safety Working Group</td>
</tr>
<tr>
<td>PCC</td>
<td>Post-combustion Carbon Capture</td>
</tr>
<tr>
<td>PGS</td>
<td>Petroleum Geo-Services</td>
</tr>
<tr>
<td>POB</td>
<td>Persons on Board (the offshore installation)</td>
</tr>
<tr>
<td>Power Technology</td>
<td>Former E.ON UK technology specialist organisation, now part of ENT.</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>PQQ</td>
<td>Pre-Qualification Questionnaire</td>
</tr>
<tr>
<td>PSR</td>
<td>Pipeline Safety Regulations</td>
</tr>
<tr>
<td>PVT</td>
<td>Pressure Volume Temperature</td>
</tr>
<tr>
<td>Ramsar</td>
<td>Generally used name for the Convention on Wetlands of International Importance</td>
</tr>
<tr>
<td>SAC</td>
<td>Special Area of Conservation</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>SHE</td>
<td>Safety, Health and Environment</td>
</tr>
<tr>
<td>SIL</td>
<td>Safety Integrity Level</td>
</tr>
<tr>
<td>SOX</td>
<td>Sulphur Oxides</td>
</tr>
<tr>
<td>SPA</td>
<td>Special Protection Area</td>
</tr>
<tr>
<td>SSSI</td>
<td>Site of Special Scientific Interest</td>
</tr>
<tr>
<td>ST</td>
<td>Steam Turbine</td>
</tr>
<tr>
<td>TBA</td>
<td>To be advised</td>
</tr>
<tr>
<td>TBC</td>
<td>To be completed / To be confirmed</td>
</tr>
<tr>
<td>TEMPSC</td>
<td>Totally Enclosed Motor Propelled Survival Craft</td>
</tr>
<tr>
<td>TR</td>
<td>Temporary Refuge</td>
</tr>
<tr>
<td>TSWG</td>
<td>Transport and Storage Working Group</td>
</tr>
<tr>
<td>UKOOA</td>
<td>UK Oil Operators Association (replaced by Oil &amp; Gas UK)</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>UXO</td>
<td>Unexploded Ordnance</td>
</tr>
<tr>
<td>v/v</td>
<td>Volume fraction</td>
</tr>
</tbody>
</table>
4. Project Design

4.1 Commentary

The Kingsnorth CCS Project

E.ON's existing coal-fired power station at Kingsnorth, on the Medway Estuary in Kent, is reaching the end of its life and is due to close by the end of 2015 under the Large Combustion Plants Directive. E.ON has submitted plans to replace it with a new, high efficiency, supercritical, coal-fired power plant designated as Kingsnorth Units 5 and 6. The new plant is designed to include a commercial scale carbon dioxide (CO2) capture demonstration plant using the best available technology, and this chapter considers the overall design of the carbon capture and storage (CCS) project and its interface with Units 5 and 6.

The power plant will be based on supercritical technology that would achieve approximately 45% net efficiency (net of the normal power plant auxiliaries but before carbon capture, and based on the Lower Heating Value of the fuel). The carbon dioxide capture and compression plant itself consumes a significant amount of power reducing the overall plant efficiency and output. The full chain CCS demonstration will capture and store the carbon dioxide from 300MW of net electricity generation after taking into account these additional losses. Because of these additional losses this is equivalent to capturing about half of the CO2 from one of the new units, which would each produce 800MW without carbon capture. The CCS demonstration is intended to capture 20 million tonnes of CO2 over a period of 10-15 years. It will be integrated into the overall design to give maximum overall efficiency for the abated power plant.

E.ON proposes to lay a 270km 36" high pressure pipeline to transport the CO2 from Kingsnorth to the Hewett gas field in the Southern North Sea, where the CO2 can be injected into a depleted gas field for long term storage. Details of the carbon capture plant, the pipeline, and the storage are covered in later chapters.

Basis of Design for the CCS Project

To ensure a common approach to the design of the CCS project ‘Design Philosophy’ documents were written, each individually covering an aspect of the design. These were intended to ensure a consistent understanding for all colleagues involved in the project. The ‘Index of the Full System Basis of Design’ lists the Design Philosophies created for the project. The system of units that would be used for design and key items of project data were also fixed at an early stage to ensure a consistent approach and are detailed in the ‘Overall Project Units’ and ‘Overall Project Data’
documents. Further items will be added to the Overall Project Data as the design progresses.

Communication at the interfaces between E.ON and the various contractors working on the project has been vital to ensure the consistent development of the overall project parameters. The ‘Interface Management Philosophy’ outlines how the interfaces between partners were managed with defined roles and working groups, and the three ‘Working Group Reports’ describe particular interface issues raised through these working groups.

**Overall Project Lifecycle**

The programme for the construction of the power plant, CO2 capture and compression plant, pipeline, offshore structure, and wells is outlined in the ‘Construction Philosophy’. This document also includes overall requirements relating to the construction works and the interface to the existing Kingsnorth Units 1-4 which are assumed to be in the process of closure and demolition during the KCCS development programme. The ‘Full CCS System Commissioning Philosophy’ follows on from this outlining the processes that will be used to bring the project from the construction phase into operation.

It is expected that the plant will be commercially operated as a baseload station in the early years of operation. As new, less responsive, entrants enter the market in the period to 2030 (wind and nuclear in particular) it is highly probable that situations will occur at times when surplus supply on the system forces reductions in load. In later life the plant is expected to move into periods of lower load operation and shutdowns at times, particularly overnight and at weekends. For the 15 year period of the CCS demonstration, it is intended to operate the power plant as a base load station without interruption whenever possible. Thus at maximum output, the CCS chain is designed to operate at 90% removal efficiency to remove 6600tpd of CO2 from the flue gas with the Power Plant at full load. The ‘Full System Operating Philosophy’ gives further detail of the anticipated operating regime of the power plant and the requirements that this will place on the CCS plant.

As the demonstration CCS plant captures half of the CO2 from one of the two new Units, consideration has been given in the ‘Future Expansion Design Philosophy’ to the possible later addition of further CCS plant to capture CO2 from the remainder of the power plant should regulations require this fitment. This has a particular impact on the plant layout, but also implications on a number of aspects of design of the whole CCS chain. Two potential layouts have been considered for the CO2 capture plant and these are shown within the two ‘Plant Layout’ drawings.

The ‘Full Chain Decommissioning & Abandonment Philosophy’ outlines the considerations for the potential refurbishment of the capture plant at the end of the demonstration period and also for the eventual decommissioning in the longer term.
of the pipeline and storage facilities. The design lives of the various elements of the chain from power plant to storage facilities are considered in the ‘Design Life Philosophy’.

Although the CCS demonstration plant captures the CO2 from about a quarter of the new Kingsnorth power station, the entire power station has been independently certified by TÜV to be ‘Carbon Capture Ready’ (which includes the enablement of CO2 capture to be fitted across the whole power station) in the ‘Carbon Capture Readiness Report’.

In support of the Consent application for Units 5 and 6 with the integrated demonstration carbon capture plant, E.ON has explored opportunities for combined heat and power (CHP), including community heating. However, the Kingsnorth site is remote from population centres and other industry, and in consequence there are no identified industrial consumers near to the site, nor are there any opportunities to provide heat to existing residential, public or light commercial users. The ‘CHP Study’ investigates multiple scenarios, but even the most favourable could not provide an attractive return on investment.

**Interface between the Carbon Capture Plant and the Power station**

Although it is intended to demolish the existing Kingsnorth Units 1-4, some of the infrastructure from the existing power station may be re-used in the new Units 5 & 6 and the carbon capture plant, in particular the cooling water infrastructure. The feasibility of re-use of infrastructure is considered in the ‘Life Assessment of Existing Infrastructure’, and further investigation of the cooling water requirements of the new plant and potential re-use of existing plant is covered in the ‘Cooling Water System Design Report’. A separate study ‘Environmental Impact of CCS Cooling BAT report’ details the various cooling technologies that could be used for the new power station and the CO2 capture plant and shows that direct cooling of the plant is the Best Available Technology from an environmental perspective.

The primary interface between the power station and the capture plant is the flue gas from which the CO2 is extracted. The ‘Power Plant Heat & Mass Balances at Various CCS Conditions’ shows the flow of flue gas from the power plant and through the capture plant at various combinations of loads on the power plant and capture plant. In addition the capture and compression plant has requirements for heating, cooling, waste disposal, and various utilities that can be advantageously interfaced with the power plant. The ‘Design report of flue gas and steam integration of power plant and capture plant’ considers the interfaces of steam, condensate, waste water, cooling water, and various utilities. The ‘Interface Design of Water Steam Cycle and CCS Process’ further considers the extraction of the steam from the steam turbine system, and the ‘Study on CCS Waste Water Use in FGD Plant’ considers how some of the waste water from the CCS plant can be advantageously
re-used in the main FGD plant. The ‘Overall Water Balance’ details all the water flows of the combined power station and CCS plant.

The ‘Overall Plant Integration Philosophy’ outlines the major areas of integration, and further integration details are covered in a range of Design Philosophy documents which consider the system requirements and potential integration of the power plant, the capture plant, and the compression plant. These provide the basis for a consistent approach to more detailed design.

The inspection and maintenance requirements for the power plant and CCS system are described in the ‘Inspection & Maintenance Philosophy’ and in particular the periodic outage and major inspection requirements which will need to be co-ordinated through the whole CCS system (including pipeline, platform and wells).

The CO2 capture plant will produce a waste sludge as part of its normal operation and a particular integration issue is whether this sludge can be disposed of by burning in the power station boiler. This issue is covered in the ‘Sludge Co-firing Report’ which concludes that this would be technically possible with suitable additional emissions monitoring although other options exist for dealing with this sludge.

**Detailed Design Philosophies for the full CCS chain**

Integration is also required along the entire CCS chain from its capture from the flue gas, through compression and pipeline transport to the injection via wells to storage. The ‘Full System Metering Philosophy’ considers the CCS metering that will be required to measure plant performance, as a means of demonstrating compliance with environmental regulation, to control flows and to provide a basis for payment.

The ‘Full System Leak Detection Philosophy’ provides a preliminary view of detection of CO2 leakage throughout the capture and transportation systems. The ‘Full System Relief, Vent & Blowdown System Design Philosophy’ considers how operational releases of CO2 from the system may be managed and the significant further work required in this area.

The communications along the pipeline and to the offshore structures are considered in the ‘Onshore To Offshore Communications Philosophy’, and some pipeline control considerations covered in the ‘Transport & Storage System Control Philosophy’.

The interface with the pipeline and how it can be started up and depressurised is covered in detail in the ‘Whole CCS System Operating Philosophy Covering Steady State & Transient Operation Flow’.
Carbon Dioxide Toxicity

Throughout the following chapters there are a number of references to the harmful or toxic effects of carbon dioxide. Carbon dioxide is widely used in our normal environment in fire extinguishers and fixed fire suppression systems, is commonly used for theatrical effects (in the form of subliming solid ‘dry ice’) and of course is part of the natural human respiratory system.

CO2 is generally understood to have an asphyxiant effect on humans and animals if there is sufficient CO2 in the atmosphere to displace oxygen. Less widely known is the CO2 can have a toxic effect in very high concentrations. Carbon dioxide can cause nausea, confusion and ultimately death if the concentration is extremely high and the time of exposure is long enough. However CO2 is not classified as toxic under the COSHH Regulations, and the term toxic is generally used for substances that have an adverse impact on health at much lower concentrations.

Further detail on the health and safety aspects of CO2 can be found in chapter 8.

Summary of Key Issues

The key aspects of the design and integration of a CCS development are:

• Power plants have been designed for many years to operate flexibly in response to the demands of the electricity network. The CCS plant technology is closer to process plant technology which is not usually designed for such flexible operation, and this will provide a key challenge during the detailed design process to provide the required flexibility of operation.

• Assessment of various cooling technologies for the power station and carbon capture plant shows that direct water cooling is the Best Available Technology in terms of Environmental Impact.

• Significant parts of the existing cooling water infrastructure can be re-used.

• There is potential to advantageously interface steam and cooling systems between the power plant and CCS plant.

• Venting, and the consequent cooling, of CO2 for pressure relief or operational reasons raises issues with lack of buoyancy and dispersion which require significant further work.

The links to the Project Design documents are repeated below:

4.2. Coordinated Index of Full System Basis of Design & Philosophies
4.3. Full System Operating Philosophy
4.4. Overall C&I System & Integration Design Philosophy
4.5. Full System Metering Philosophy
4.6. Full System Leak Detection Philosophy
4.7. Construction Philosophy
4.8. Inspection & Maintenance Philosophy
4.9. Future Expansion Design Philosophy
4.10. Full Chain Decommissioning & Abandonment Philosophy
4.11. Interface Management Philosophy
4.12. Overall Project Units
4.13. Utilities Philosophy
4.15. Whole CCS System Operating Philosophy Covering Steady State & Transient Operation Flow
4.16. Overall Project Data
4.17. Full CCS System Commissioning Philosophy
4.18. Transport & Storage System Control Philosophy
4.19. Onshore To Offshore Communications Philosophy
4.20. Civil Design Philosophy
4.21. Onshore Electrical Design Philosophy
4.22. Cooling Medium System Design Philosophy
4.23. Steam System Design Philosophy
4.24. Drains System Design Philosophy
4.25. Instrument Air System Design Philosophy
4.26. Design Philosophy for Chemical Injection Systems
4.27. Fire and CO2 impact design philosophy
4.28. Emergency Shutdown System Design Philosophy
4.29. Construction Logistics and Access Philosophy
4.30. Overall Plant Integration Philosophy
4.31. Craneage Lifting and Handling Design Philosophy
4.32. Sludge Co-firing Report
4.33. Study on CCS Waste Water Use in FGD Plant
4.34. Power Plant Heat & Mass Balances at Various CCS Conditions
4.35. Design report of flue gas and steam integration of power plant and capture plant
4.36. Life Assessment of Existing Infrastructure
4.37. Transport & Storage Working Group Report
4.38. Plant Layout with Compact Carbon Capture Demonstration Plant
4.39. Plant Layout with Split Carbon Capture Demonstration Plant
4.40. Overall Water Balance
4.42. Interface Design of Water Steam Cycle and CCS Process
4.43. Environmental Impact Study regarding CCS Cooling
4.44. Full System Relief, Vent & Blowdown System Design Philosophy
4.45. CHP Feasibility Study
4.46. Operational Safety Working Group Report
4.47. OPAPP Working Group Report
5. Technical Design
   Carbon Capture and Compression

5.1 Commentary

Capture and Compression Plant Design Requirements

The 'Design Basis for CO₂ Recovery Plant' lists the design parameters relating to the capture plant site, the flue gas to be treated, the utilities available, the required life and availability of the plant, and other constraints to be complied with in the capture plant design. Current experience in carbon capture plant is described, and also the technology used to capture the CO₂ from the flue gas which is introduced with a description of the quencher, the absorber column to capture the CO₂ and the stripper column to release the CO₂ from the solvent for subsequent compression and introduction into the pipeline.
The quencher takes the flue gas from the power plant and passes it through a final stage of desulphurization and wet electrostatic precipitation, and finally washing and cooling to prepare the flue gas for the absorption stage. The absorber captures the CO₂ from the flue gas by adsorbing it into an amine solvent. The flue gas is then washed which removes any remaining solvent before returning the flue gas to the power plant for exhaust via the chimney. The CO₂ rich amine solvent is then circulated to the stripper/regenerator column where the solvent is heated and the CO₂ released from the solvent, allowing the solvent to be re-circulated to the absorber for reuse.

The CO₂ released from the capture plant is at around 30°C and just above atmospheric pressure, and therefore requires compression before transportation via the pipeline to the storage site. In this demonstration project the CO₂ is compressed to 30-40 bar for entry into the pipeline, but must remain at a temperature of no more than about 40°C. Cooling is therefore required between and after compressor stages to achieve this. It is vital that the CO₂ is dried before pipeline entry (to avoid pipeline corrosion and ensure CO₂ quality for field entry). In consequence a dehydration plant is planned after compression which will reduce the water content from around 2.9% (by volume) to 24ppm. These requirements are further detailed in the ‘CO₂ Compression and Dehydration Design Basis’ and the ‘CO₂ Compression and Pumping Philosophy’.

It is intended that the CO₂ will pass directly from the capture plant through compression and dehydration and into the pipeline without any storage of CO₂ on site. However under some scenarios it is possible that some on-site storage of CO₂ could be required, and these scenarios are briefly discussed in the CO₂ Intermediate Storage Philosophy.

**Details of the Capture and Compression Plants**

The details of the processes of capture, compression, and dehydration are best visualised on the Process Flow Diagrams (PFDs) which show the process flows described above together with additional detail of coolers, pumps, and other plant items. Separate PFDs are provided for the capture plant, the compression plant, and the dehydration plant to show the complete flue gas and CO₂ flows.

The process conditions at points on the PFDs marked with numbered diamonds are shown in the material and heat balances. These show the pressures, flows, temperatures, and composition details of the main process flow streams for three different plant load conditions: full boiler load (100%), 60% boiler load, and a minimum boiler load of 25%. One set of balances cover the capture plant and the other covers the compression and dehydration plants.
The flue gas taken from the power plant is returned to a point in the flue gas ducting just downstream of its extraction point, consequently the flue gas blower shown on the process flow diagram is required to drive the flue gas flow through the quencher and absorber. There are two separate water circuits shown in the quencher with separate extractions of excess water. These have been separated because the recovered quench water is of good enough quality for re-use on the power station, whilst the deep FGD waste water is sent to the water treatment plant.

The various processes of the capture plant operate optimally at different temperatures and hence heat exchangers are used to increase or decrease the flow temperatures to optimise. Where possible, heat is exchanged within the capture plant, for example between the two solvent streams entering and leaving the regenerator column. Other heat exchangers cool streams with cooling water and elsewhere the potential of recovering some of this heat for use in the power plant is discussed.

Low Pressure (LP) steam supplied from the power plant is used to provide heat in the solvent regenerator reboiler and Intermediate Pressure (IP) steam is used to provide heat in the solvent reclaiming system. The condensate from both processes returns to the power plant and these streams are also shown on the capture process flow diagram and the material and heat balance.

The process for compression up to 40 bar in the demonstration project comprises four stages with inter stage coolers and knockout vessels to remove water. For later phases of the project when the pipeline transportation changes from vapour phase to dense phase CO₂ it is anticipated that two further stages of compression will be required (these are not shown on the PFDs provided).

Following compression, the CO₂ stream is dehydrated using molecular sieves and filtered before passing to the export pipeline. The molecular sieves are periodically regenerated and the wet CO₂ produced returned to the compression plant; the heat for this process is provided by a heat exchanger which condenses IP steam from the power plant.

There is some further information on the major plant items shown on the process flow diagrams is provided in the Equipment Lists, showing the size and duty of plant items.

The plant layout drawings in this chapter show a plan view of the layout of the flue gas path from the boiler to the chimney, and of the capture and compression and dehydration plant. Two possible plant layouts are shown, the “compact” plant layout in which all of the capture and compression facilities are located together alongside the boiler, and the “split” layout where the quencher and absorber are moved to a location close to the chimney. The compact plant requires long flue gas ducts but has a short solvent circuit as the absorber and stripper (regenerator) are located in close proximity. The split plant layout only requires short flue gas ducts but has a
long solvent circuit between the absorber and stripper. Of these two layouts the split plant layout is preferred.

The degree of information made available in the PFDs, the material and heat balances, the layout drawings, and the equipment lists has been limited in order to protect the commercially sensitive information of the participants.

**Key Learnings**

- Quench water can be reused in the power plant should be kept separate from the desulphurisation waste water;
- Molecular sieves have been selected as the most appropriate equipment for dehydration of the CO₂ prior to pipeline transportation;

With the particular layout constraints of the Kingsnorth site, a split layout of the absorption and regeneration equipment is preferred over the compact layout.

The links to the Technical Design – Carbon Capture & Compression documents are repeated below:

5.2. **CO₂ Compression and Pumping Philosophy**
5.3. **CO₂ Intermediate Storage Philosophy**
5.4. **Design Basis for CO₂ Recovery Plant**
5.5. **Material and Heat Balance for CO₂ recovery plant - 100% boiler load case**
5.6. **Material and Heat Balance for CO₂ recovery plant - 60% boiler load case**
5.7. **Material and Heat Balance for CO₂ recovery plant - 25% boiler load case**
5.8. **Process Flow Diagram for CO₂ Recovery Plant**
5.9. **CO₂ Capture Unit - Major Component Equipment List**
5.10. **Plant Layout Drawings - Compact Plant Layout**
5.11. **Plant Layout Drawings - Split Plant Layout**
5.12. **CO₂ Compression and Dehydration Design Basis**
5.13. **100% Boiler Load Heat and Material Balance**
5.14. **60% Boiler Load Heat and Material Balance**
5.15. **25% Boiler Load Heat and Material Balance**
5.16. **Gas Phase CO₂ Compression Process Flow Diagram**
5.17. **CO₂ Dehydration Process Flow Diagram**
5.18. **CO₂ Compression - Sized Equipment List**
5.19. **Oxygen Content Reduction Study Report**
5.20. **Pipeline integration study**
5.21. **Dense Phase CO2 Compression Process Flow Diagram**
5.22. **CO₂ Compression Unit - Cooling Water Distribution Process Flow Diagram**
5.23. **CO₂ Compression and Dehydration Utilities Process Flow Diagram**
6. Technical Design
Pipeline and Platform

6.1 Commentary

This chapter of the KKRB is devoted to the transportation and injection infrastructure requirements of the Kingsnorth Carbon Capture and Storage (KCCS) development. In simple terms, this encompasses a 36” (outside diameter) pipeline which runs onshore for approx 10 km and offshore in the Southern North Sea for 260 km, a platform in the vicinity of the Hewett field location, and appropriate facilities for the processing of the CO2 stream prior to injection into the sequestration site.

Background Philosophy

All aspects of establishing an agreed philosophy for design and operation of a storage and transport system for CCS begin with understanding what the initial flowing conditions will be at the interface between the well perforations and the reservoir (i.e. at the sandstone face at the bottom of the well). The target geological structure sets the initial boundary pressure condition for flow assurance analysis in all components of the chain from a sphere of sandstone near the bottom of well perforations; back through downward flow in the well tubing; to the wellhead; to the pipeline delivery pressure at the offshore location to the pipeline inlet pressure. Flowing conditions in every segment of the transport system right the way back to the inlet pressure of compressors at the power station is determined by the initial pressure of the target CO2 reservoir.

In this study for the Kingsnorth project, the proposed target of the Lower Bunter reservoir at Hewett will start its life at a very low pressure (around 3 bara). We are informed by studies carried out by Baker RDS into the nature of the Lower Bunter reservoir (see Chapter 7) that, the field pressure will only increase modestly to around 31 bara (avg), over the expected injection period of 12 to 15 years. The injection period is calculated on the basis of a required injection rate of 6,600tpd, ultimately storing the demonstration volume of 20 million tonnes of CO2). This compares with the original pressure in the reservoir when it was initially discovered and containing natural gas of just over 122 bara (hydrostatic pressure at the top of the structure). Now that the field is fully depleted we are able to see that there is no noticeable tendency for the field to return by natural migration of aquifer (water).
NOTE; Phase Behaviour of Fluids in Transport Systems (This note is provided for the benefit of non technical readers):

Design for transport of fluids (liquids or gases) in transport systems almost always needs to consider vapourisation of components/fractions in the flowing liquid or condensation of components/fractions of the flowing gas. Where either of these conditions occurs, the resulting flow is referred to as two phase flow. Two phase flow is almost always less efficient compared with flow that is designed to remain in a single phase of vapour or liquid and there are precautions which must be included in the pipeline design to avoid loss of flow control and/or the impact of forces similar to “water hammer”. Two phase flow is allowed in some transport systems including for crude oil and unprocessed natural gas, but only under rare circumstances and with precautions being included in the design.

For the purposes of the conceptual design work described in chapter 7 and 8 of this KKRБ all flowing systems for CO₂ transport were considered to operate in a single phase flow – vapour phase flow for the demonstration period and liquid phase flow for the periods following the demonstration. The reason for this is that there is considered to be insufficient information and software available to properly analyse the flowing conditions of CO₂ in two phase flow in either pipelines or wells.

It is possible that downward flow of CO₂ in wells in a two phase flowing condition could offer some injection operations efficiencies (a reduced heating energy demand) if this flowing regime were better understood. This may be a future research opportunity.

Consequent assumptions

In summary, the target sink is a very large empty pressure containment device sitting at a low pressure. Importantly, the field pressure will remain below that of the critical pressure of CO₂ (73.7 bara) after the demonstration volumes have been injected. This leads to a number of very important conclusions in relation to pipeline transport:

i  Pipeline flow throughout the demonstration period can be conducted wholly in vapour (gaseous) phase provided that the pipeline is large enough in diameter to maintain pipeline pressures beneath the level at which condensation may occur (liquid forming in the pipeline). The benefit is that this will minimise the amount of energy needed in the conditioning of the CO₂ for transport i.e. no liquefaction or increased compression requirement.

ii  Maintaining vapour phase for the demonstration will also minimise the energy that would be needed at the offshore location to condition the CO₂ for injection i.e. reheating liquid CO₂ to vapour to ensure the single phase flow in the well would not be necessary.
Accepting the above means that the demonstration platform size and associated cost could be minimised (space requirements are reduced), much of the power and energy requirements are avoided (reducing additional CO2 emissions) and the risks, complexities and uncertainties (and costs) of transport by dense phase flow can be minimised. Combined, these things also aid the possibility of developing an injection operation which uses a NUI (Normally Unmanned Installation).

Insofar as the pipeline and platform system are concerned, the broad, most important, fundamental and explicit assumptions that the KCCS design team started with are captured in iii) above.

**Platform Concept Selection**

The platform concept which is recommended for the KCCS offshore facility is a liftable jacket substructure with a lift-installed integrated deck topsides structure and piled foundations. Work completed during FEED 1a has confirmed the viability of the other explicit assumptions related to a vapour phase transport solution:

i. The platform size for the demonstration can be minimized to an NUI that needs to be large enough to accommodate no more than 4 wells with one relatively small start up heater per well.

ii. Heating equipment and heating load can be kept to a minimum with no other flow conditioning or process equipment being required.

**Transport Solution Selection**

In the months prior to the preparation of E.ON’s Bid into the CCS Demonstration Competition in late 2009, the Transport and Storage (T&S) design team had calculated the relative energy cost of all the significant alternative methods of transport and injection including dense phase pipelines, vapour phase pipelines, and two different methods of dense phase shipping. These studies had demonstrated that a vapour phase transport solution was optimal from an overall cost perspective.

The pipeline size selected for study was 36 inch OD (Outside Diameter). A pipeline wall thickness of up to around 40mm was assumed (leaving an internal diameter available for sustaining flow of around 32 to 33 inches). A number of alternative pipeline routes were identified for the onshore and offshore sections. Eventually pipeline route surveys conducted with the assistance of RSK and Fugro would determine the operational safety management and the construction challenges associated with each route and inform the efforts to narrow down the alternative potential routes to one preferred combined route. It is important to say that the land route selection decision was dominated by consideration of the route with the
minimum number of domiciles within a 1 km corridor. The selected onshore route has eight domiciles within the 1 km corridor.

The overriding issues influencing the offshore route (corridor) selection were minimising the impact on inshore fishing, reducing the risk of encountering sunken ships (wrecks), avoiding gravel mining operations, avoiding wind farm license areas and avoiding established anchorages for shipping. After surveying the preferred offshore route corridor more detailed alignment drawings have been prepared. However, it is most important to note that another survey of the route will be required immediately prior to construction to confirm that the EIA for the selected route remains valid.

Pipeline Key Issues

A number of significant issues are noteworthy of further comment in relation to pipeline design and operation:

i  The pipeline material selected and recommended is high yield strength carbon steel. Despite the known corrosion problems associated with CO₂ there is no need to consider the use of exotic stainless steels or corrosion resistant materials for the line pipe. CO₂ is not corrosive on its own account. Water must be present with the CO₂ to form carbonic acid for CO₂ to be corrosive. The corrosion prevention strategy is to provide a high reliability drying process to the captured CO₂ flow stream immediately downstream of compression and upstream of the pipeline inlet. Monitoring systems will inform instrumentation to shutdown the pipeline inlet in the event that the required level of dryness is not being achieved by the drying equipment.

ii  The pipeline can only be operated as a vapour phase pipeline until the pressure at discharge from the compressors reaches 39 barg. This will be consistent with a flowing pressure at the wellhead injection pressure of 35 barg and an injection pressure at the reservoir (BHP) of less than 33 barg when flowing at a rate of 6,600tpd. This will not occur until after the field has received well over 22 million tonnes of injected CO₂. These performance criteria are based on a recommended design details identified for wells and pipeline.

iii  The costs of materials and installation of a larger pipeline required to sustain vapour phase flow throughout the demonstration period (through limiting pressure loss and therefore pressure in the pipeline) are more than offset by:

   (1) reduced equipment cost,
   (2) reduced infrastructure costs,
   (3) reduced energy costs,
   (4) reduced manning and operating costs,
(5) technical risk & project risk avoided, and,

(6) the reduced costs of safety management associated with a dense phase pipeline transport operation.

iv The pipeline route passes within 1.5 km of the known location of a shipwreck (SS Richard Montgomery) located in the mouth of the Medway estuary. This wreck was known to contain unexploded ordnance (UXO) when it sank in the 1940’s. A hazard assessment has been undertaken and this is contained within the design risk register among other assessments carried out during conceptual design. It should be noted that a thorough risk assessment in relation to the possibility of danger presented by this shipwreck needs to be carried out in co-operation with the pipeline installation contractor early in contractor engagement and continually reviewed when barge anchor patterns are being decided on for the finally confirmed route.

Pipeline Pre-Commissioning

The testing and drying philosophy and commissioning reports have not finally identified the method to be used for drying the pipeline following hydro-testing. Water remains the only viable medium for strength testing of the pipeline after it has been constructed/ laid. The recommendations of this study have identified compressed and dried air as one medium that could be used to finally dry the pipeline before CO₂ is to be permitted to enter the pipeline. Similar large pipelines that are used to transport CO₂ rich natural gas are dried over the first months of their operation by using the natural gas (which has been dried at its point of production) to “mop up” residual test water. The arrival of “wet” gas at terminals that receive large quantities of natural gas is tolerated for the period (say 6 months) that it takes to get the pipeline dry. While the method would successfully dry the pipeline, the “wet” CO₂ cannot be injected into the storage reservoir. It is currently felt among reservoir and well engineers that the presence of water would damage the well or the reservoir in the early stages of injection. Clearly, a compromise needs to be found so that pipeline commissioning costs can be estimated with more certainty and an agreed approach can be developed on an industry wide approach.

Injection Temperature

One of the consequences of selecting a depleted natural gas production reservoir as a storage site is that flow into the reservoir needs to be controlled by a device that will throttle pressure (a choke valve). Throttling of gases from a higher pressure to a lower controlled pressure/flow rate is always accompanied by significant temperature loss. It seems intuitively obvious that temperatures below zero (in the well) are something to be avoided to avoid freezing of water. Not only is there a possibility that there is water present in the pores of the sandstone especially at the beginning...
of injection or after a long period of no flow, it is also certain that there will be water present in the annulus spaces of wells and likely that water will sometimes infiltrate into the sump of the well during periods of no flow (the sump is the length of the drilled hole below the perforations).

The intuitive position that it would be wise to maintain temperatures above 0 deg C in the well was supported by specialist reservoir and well engineering advice from Baker RDS which would avoid both water freezing and hydrate formation in the flowing CO₂. In the absence of specific injection testing information, maintaining a temperature above 0 deg C was adopted as the “safe” option.

Flow assurance calculations therefore paid much attention to the changing temperature of the transported CO₂ along the length of the transport chain to the sand face. Calculations were conducted for both dense phase flow and vapour phase flow. The net outcome of calculations using the various models is that process heating at the wellhead choke can be avoided for the vapour phase flow under steady state (and slowly changing) flowing conditions. However, a very large and continuous heating load equivalent to around 20 MW (around 6 to 7 MW per well) of electrical heating demand will be required to support injection into the well from the lowest dense phase flowing pressures at the beginning of the field life.

However, the decision to pursue vapour phase flow for the demonstration period is not free of heating. Heating will be required for some startup conditions at a maximum power rating of 2 MW. This is not a continuous demand and some startup operations can be conducted without heating being necessary at all. Startup heating is unavoidably required when starting to flow following a pipeline shutdown where the pipeline is closed in and average flowing pressure needs to be released into a low pressure, non flowing well. While startup heaters will always need to be provided, operating methods will be able to be developed to minimise the use of them.

For the purposes of the demonstration we have assumed that the 2 MW (maximum) heating load will be supplied by electricity via cable from shore. This minimises fuel use and storage on the NUI. For simplicity, considerations of expansion of the facility at a time after the demonstration has been completed or for comparative cost estimates we have assumed that the higher heating loads required for dense phase operation at the same or higher flow rates will also be supplied by electricity from shore. However, the studies and the debate over the choice between electrical energy supply and gas energy supply for these future (up to around 80MW power demand scenarios are still to take place.

Emergency Shutdown

There are a number of emergency (and other) shutdown scenarios to work through during later stages of FEED to design/select systems and/or operational instructions
that will mitigate any hazards identified by various HAZID workshops and by
designers themselves. Emergency shutdown systems will be tested at the end of
FEED and during detailed designs by HAZOP procedures. What is important to note
here are two aspects of the ESD system that are likely to challenge first expectations
and/or common practice, these are:

i Any CO2 pipeline which supplies an offshore platform should not
automatically be fitted with a Sub Sea Isolation Valve (SSIV). This is common
practice for offshore oil and/or gas pipelines and has been since the Piper
Alpha disaster. However, as CO2 is not flammable and therefore cannot feed
a fire on an offshore installation, and an SSIV in a CO2 pipeline could create
problems as a leak or corrosion weak point, (or with pipeline start up after a
closure), it has been decided not to include an SSIV in the design.

ii In some instances, it may be more appropriate for an emergency pipeline
shutdown response to be arranged so that only some pipeline valves move to
the closed condition. There may be clear advantages, when stopping flow
into the transport pipeline (for whatever reason) in keeping the pipeline outlet
valve and well valves open so that the pipeline pressure equalizes with the
reservoir pressure following shutdown. This approach can reduce time and
energy costs in a re-start, and since CO2 flow into the well is a completely
different situation to that under consideration in oil and gas production, it could
be advantageous to challenge established common approaches to wellhead
systems design.

Personnel Safety

Similarly, there are some aspects to management of personnel safety and the design
of escape and refuge facilities that will benefit from a design approach that
challenges the established practice used in designs and operational practices for oil
and gas pipelines and platforms. It is very clear that sending a helicopter to
investigate a possible major loss of CO2 containment at an offshore location may
require the pilot to consider (and be trained to consider) the specific threat that an
invisible cloud of inert gas might pose to the operation of a helicopter turbine.
Another example of a similar area for caution would be in the design and use of
offshore escape systems under circumstances where a dispersing but invisible and
falling denser-than-air CO2 cloud might present a hazard to surface craft such as
standby vessels and/or traditional escape craft. These and other matters will be
significant issues that will need to be addressed in subsequent FEED and detailed
design activity. Such matters will need to be considered for both emergency and
non-emergency relief and blow down operations and in the design for relief and blow
down activities. All these issues are covered in some detail in the following reports
giving regard to the modelling of dispersion plumes under various blow down and loss of containment scenarios.

**Venting**

Venting is another type of emission to atmosphere which is separate to but similar to blow down insofar as it involves an intended release to atmosphere from locations within the power station and in particular, from the capture, compression and drying/cooling systems and pipe work. Venting of “off specification” CO₂ will need to be a common feature of start-up and turn-up operations. In order to conduct the various venting operations it was decided to make use of the height and location of the flue gas chimney stacks. Venting will make the design of the stacks more complex and capable of dispersing flue gases and CO₂ vented from a number of different source conditions. The increased complexity required of future flue stacks will present a challenge to designers of the venting and dispersion systems. The systems produced will also provide facilities for the safe dispersion of emergency and non emergency blow down of pipe work and at least some of the pipeline system.

**Flow Assurance Modelling**

The following chapter 8 includes the steady state and transient flow analysis reports which provide a major contribution to Flow Assurance. The reports are necessarily highly technical. The results of modelling described in the reports and have lead to the adoption of a number of refinements to the base case to be used in design going forward. Some of these refinements include:

- **i.** An informed assumption that intermediate storage for CO₂ may not be required for transport systems that are wholly (or partly) made up of a large capacity pipeline system which is operating in vapour phase. Where the pipeline or part pipeline is directly connected to the power station capture and compression plant, compressibility in the vapour content of the pipeline can be used as a substitute for at least some intermediate storage. It is believed from calculation that there would be sufficient flexibility in the base case operation of the Hewett pipeline to be able to adequately control pipeline flows under transient flow conditions and some stop/start operating scenarios. Hence, the chosen base case for the demonstration is unlikely to need intermediate storage for CO₂. This whole situation changes when the pipeline system is changed to dense phase operation either for the demonstration or in any post-demonstration scenario.

- **ii.** Two phase flow in the pipeline (flow of vapour and liquid together) should be avoided as this has potential to set up transients that may damage the pipeline mechanically.
iii. While inlet temperatures to the vapour phase pipeline operation can be allowed to be as high as 50 deg C (lessening the cooling load on the power station), there is some evidence (which needs verification) that flow in dense phase may become unstable at pipeline inlet temperatures above 40 Deg C.

iv. Stop/Start operations (flexible generation, two shifting) represent a considerable challenge to CCS as the CCS system will need to follow generation flexibility. Solutions to these challenges will be much easier and less expensive to find for the base case vapour flow transport scenario that for dense phase CO2 transport scenarios.

v. 36” OD is the smallest pipeline size that will support the whole demonstration period (20 million tonnes injected over 12 to 15 years) with transport operations being wholly in vapour phase. After injection of around 22 million tonnes, the pipeline (and injection systems) will need to have been made ready for conversion to flow in dense phase.

vi. When wellhead pressures reach 35 barg there is a danger of CO2 starting to condense in the pipeline at undersea locations where the temperature is lowest – winter and summer).

vii. CO2 pipe work located on the topsides upstream of the wells will need to be insulated during winter operations when air temperature can be well below that of the sea temperature.

Summary
Throughout the execution of the work described in this chapter significant opportunity was taken to ensure that the interfaces from capture (and compression) to pipeline/platform and to wells/storage were managed closely. This was achieved by cross system interface management meetings organized to consider interface issues and to compare issues raised in separate HAZIDs. The purpose of conceptual design has been to identify the problems to be addressed comprehensively by the next stage of FEED and this suite of reports provides valuable insights to the challenges faced.

The links to the Technical Design – Platform & Pipeline documents are repeated below:

6.2. Platform & Pipeline Basis of Design for Studies
6.3. Platform and Pipeline Operating Philosophy - Gaseous Phase Operation
6.4. Onshore Pipeline Project Data
6.5. Offshore Pipeline Project Data
6.6. Onshore and Offshore Pipeline Design Philosophy
6.7. Pipeline Material Selection, Corrosion Protection and Monitoring Philosophy
6.8. Pipeline Testing and Drying Philosophy
6.9. Pigging Philosophy
6.10. Offshore Infrastructure Project Data
6.11. Structural Design Philosophy
6.13. Heating System Design Philosophy
6.15. Drains System Design Philosophy
6.16. Offshore Instrument Air Systems Design Philosophy
6.17. Fire and CO2 Impact & Prevention Design Philosophy - Pipeline and Offshore Installation
6.18. Offshore Emergency Shutdown System Design Philosophy
6.20. Offshore Mechanical Equipment Selection Philosophy
6.21. Offshore Supply and Logistics Philosophy
6.22. Platform & Pipeline Escape and Emergency Response Philosophy
6.23. Equation of State Prediction of Carbon Dioxide Properties
6.24. Steady State Analysis (Pipeline)
6.25. Transient Analysis - Start Up (Pipeline)
6.26. Transient Analysis - Depressurising and Venting (Pipeline)
6.27. Preliminary Offshore & Pipeline Control System Specification
6.29. Preliminary I/O Subsystem Estimate (Gaseous Phase)
6.30. Overall System Network Diagram
6.32. Transient Analysis - Ramp Up and Line Pack (Pipeline)
6.33. Topographical Survey Specification
6.34. Pipeline Route, Geophysical and Geotechnical Survey Report
   6.34.1. Pipeline Route Geophysical and Geotechnical Survey Report
   6.34.2. Pipeline Route Geophysical and Geotechnical Survey Alignment sheets
   6.34.3. Pipeline Route Habitat Survey Report
6.35. Offshore Pipeline Route Selection Report
6.36. High Level Field Layout Alignments
6.37. Approaches at Kingsnorth Platform Subsea Layout
6.38. SS Richard Montgomery Hazard Assessment and Management Report
6.39. Offshore Concept Screening Report
6.41. Materials Selection and Integrity Protection Report for Offshore Infrastructure
6.42. Interface Report CO₂ Pipeline & Wells
6.43. Heater Option Evaluation & Concept Design Report (Gaseous Phase)
6.44. Start-Up & Shutdown Requirements Report (Gaseous Phase)
6.45. Offshore Venting and Dispersion Study Report
6.46. Offshore Design Temperature & Pressure Report
6.47. Primary Substructure Concept Selection Report
6.48. Primary Topsides Structural Concept Selection Report
6.49. Platform Control and Shutdown Philosophy (Base Case)
6.50. Offshore Control System Philosophy
6.51. Offshore ESD System Philosophy
6.52. Transient Analysis – Pigging
6.53. Materials Selection for HSE Submission
6.54. Hydrate Mitigation Study Report
6.56. Platform and Pipeline Commissioning Philosophy
6.57. Onshore Pipeline Mechanical Design Report
6.58. Pre-commissioning and Commissioning Strategy and Plan
6.60. Heat & Mass Balance diagrams - Demo Phase (Base Case) & Full Flow
6.61. Design Temperature and Pressure Demarcation (Base Case) PFD
6.62. Overall Platform ESD Hierarchy Diagram
6.63. Pipeline HAZID/ENVID Report
7. Technical Design
Wells and Storage

7.1 Commentary

Introduction
This chapter contains the results of studies into the undersea storage reservoir for CO₂, the Lower Bunter sandstone of the depleted Hewett natural gas field. It also includes the design recommendations for the new injection wells which will deliver the CO₂ into the reservoir, and recommendations for abandonment of the existing Hewett production wells. This part of the FEED has principally been carried out by Baker-RDS, specialist subsurface and wells consultants, and their reports are included in this section of the Key Knowledge Reference Book.

This Technical Summary addresses the following aspects of the wells and reservoir:

- Storage Reservoir integrity and capacity;
- Construction and completion of wells;
- CO₂ properties and injectivity;
- Abandonment of existing and new wells;
- Monitoring;
- Hazard Identification (HAZID) and Risk Assessment;
- Key Learning Points.

The CO₂ injection is proposed in two stages. An initial “Demonstrator” stage is proposed for 12 years, when the CO₂ will be transported and injected in the gaseous phase. In the following flowing phases, the CO₂ is transported in dense & liquid phase for a further 28 years, allowing for injection at higher flow rates.

The work carried out to date represents the first stage of FEED (Front End Engineering Design) and has identified areas that require further development as design proceeds. These are noted in the following sections.

Phase Behaviour of Fluids in Transport Systems (This note is provided for the benefit of non technical readers):
Design for transport of fluids (liquids or gases) in transport systems almost always needs to consider vapourisation of components/fractions in the flowing liquid or condensation of components/fractions of the flowing gas. Where either of these conditions occurs, the resulting flow is referred to as two phase flow. Two phase flow is almost always less efficient compared with flow that is designed to remain in a single phase of vapour or liquid and there are precautions which must be included in the pipeline design to avoid loss of flow control and/or the impact of forces similar to “water hammer”. Two phase flow is allowed in some transport systems including for crude oil and unprocessed natural gas, but only under rare circumstances and with precautions being included in the design.

For the purposes of the conceptual design work described in Chapter 7 and 8 of this KKR8 all flowing systems for CO₂ transport were considered to operate in a single phase flow – vapour phase flow for the demonstration period and liquid phase flow for the periods following the demonstration. The reason for this is that there is considered to be insufficient information and software available to properly analyse the flowing conditions of CO₂ in two phase flow in either pipelines or wells.

It is possible that downward flow of CO₂ in wells in a two phase flowing condition could offer some injection operations efficiencies (a reduced heating energy demand) if this flowing regime were better understood. This may be a future research opportunity.

Storage reservoir integrity and capacity

The Hewett natural gas reservoirs are deep sandstone formations comprising the Upper Bunter, Lower Bunter and the Zechsteinkalk/Leman Sandstone. These strata exist in a dome-shaped anticline structure bounded by faults. The reservoir formations are capped and surrounded by impermeable claystone strata. A small neighbouring field - Little Dotty, producing from the Upper Bunter, may be in continuity with the Hewett Lower Bunter depending on the position and permeability of the geological fault lying between them.

The Lower Bunter sandstone has been identified as most suitable for CO₂ storage. It is typically 25m thick and lies about 1300m below sea level.

Whilst the FEED study has concentrated on the Lower Bunter as the proposed reservoir, there was a requirement to account for potential future use of the Upper Bunter for CO₂ injection. The CO₂ “storage complex” is defined to also include the Upper Bunter and Little Dotty reservoirs at this stage. The injection wells have been initially located in the south-east of the Hewett field which seems to offer the best potential for injection into both reservoirs, but other locations should also be investigated. Further appraisal work is also required to evaluate the suitability of the Upper Bunter for CO₂ storage.
The integrity of the storage complex depends on both its natural boundaries (caprock and faults) and the potential leakage pathways of the existing and proposed wells which penetrate it from the seabed. A study into the mobility of CO₂ through the overburden and boundary faults concluded that migration was very unlikely under the proposed range of injection pressures, confirmed by the fact that the Hewett field has proved an effective natural reservoir for trapping natural gas for which there is no evidence of natural migration to the surface. All studies carried out by Baker RDS confirmed that the seal integrity/reliability of the multiple caprock layers in the overburden above the Bunter structures and the seals at faults are very high. Abandoned wells were also evaluated and shown to be effectively sealed as long as they were adequately plugged. It is possible that some migration between the Upper and Lower Bunter may take place through the abandoned wells and one of the abandoned legs of one producing well but this will be contained within the storage complex (see also “Abandonment” below).

The storage capacity of the reservoir depends on its size, the porosity of the rocks and the maximum pressure that can be held without leakage. Based on well records, cores and logs from the initial development of the Hewett field, together with geophysical survey data, a 3D geological model of the Lower Bunter and Upper Bunter reservoirs has been developed. This model was calibrated for gas permeability using the Hewett natural gas production history, and then used to predict the capacity and pressure for the injected CO₂ (into the Lower Bunter only) for the demonstration stage.

To prevent migration of CO₂ through the caprock, the pressure must not be allowed to exceed either the hydrostatic (pore water) pressure or the capillary pressure threshold of the overlying caprock. The capillary pressure threshold is the point at which gas pressure overcomes the surface tension of the water held in the pores of the rock. The study estimated the capillary pressure threshold (for CO₂) of the Lower Bunter caprocks to be 133 bar. The initial pre-production hydrostatic pressure at the crest of the reservoir was only 122 bar. Therefore, if the pressure for CO₂ injection is limited to 122 bar, the risk of migration will be mitigated.

The relative permeability of the Lower Bunter formation (as assumed from reservoir modelling during production and as seen as in core samples taken during production drilling) is very high and this will provide favourable conditions for CO₂ injection if the observed conditions and assumptions can be confirmed by injection trials.

The injection modelling estimated the total capacity of the Lower Bunter reservoir at a limiting pressure of 122 bar to be 206 million tonnes of CO₂. At the end of the 12 year demonstrator stage, the average reservoir pressure in the Lower Bunter will be an estimated 31 bar. After an assumed 40 year injection programme the pressure will be at an estimated 91 bar which corresponds to an assumed total injection of 110 million tonnes of CO₂, i.e. 53% of the total capacity.
It is noted that no injection trials are currently proposed to validate the assumptions on the porosity and injectivity of the reservoir, but it is recommended that this should be reconsidered in the next stages of design. Additionally, it should be noted that the data acquisition to enable this analysis to take place was a major challenge. The data quality of some data sets was poor and additional data was provided by the site operator.

**Construction and completion of injection wells**

The number of injection wells required for the 12 year demonstrator phase is three plus one contingency well (four in total), and will be capable of injection of up to 6,600 tonnes/day CO$_2$ in gaseous phase. The phase of injection, which is assumed to take place after the demonstration phase as has been completed, requires eight wells plus one contingency well (nine in total) and will be capable of injecting 24,600 tonnes/day CO$_2$. The injection points need to be separated by approximately 3000ft in the Lower Bunter to operate effectively, and this will be achieved by drilling an array of wells from the platform position, inclined outward to a maximum of 60° from the vertical. Flow modelling has shown that the required injection rate can be efficiently achieved using 7” diameter tubing.

Following natural gas extraction, the Hewett Lower Bunter reservoir is currently at a very low bottom hole pressure of less than 3 bar. When drilling into a depleted hydrocarbon reservoir, the stability of the drillhole must be carefully maintained and there is a risk that the low pressure may allow drilling mud to seep into the formation, blocking the pores and reducing CO$_2$ injectivity. This can be mitigated by controlling the drilling mud density and hole inclination. Fortunately the Bunter sandstones do not appear to be prone to instability, as is apparent from more recent wells drilled into the depleted Lower Bunter. Further testing on cores of the Bunter sandstone is recommended to confirm the permeability and strength assumed for initial design.

Completion of the injection wells can be executed with standard oil and gas industry components of suitable specification. The objective of the well completion design is to minimise formation damage and potential leak paths, as well as provide a system suitable for both gaseous phase and dense phase CO$_2$ injection. However, further work is required to investigate whether the wells should be designed for future injection into the Upper Bunter.
**CO₂ properties and injectivity**

CO₂ is corrosive to steel in the presence of water, with the risk of hydrate formation possible at low temperatures. The design assumes the CO₂ arriving from the pipeline is 99.94% pure with minor constituents of nitrogen and oxygen and importantly, a very low water content of 0.0024% (0.01% transient). The study has shown that as long as the water content of the delivered CO₂ is maintained below 0.03% then hydrate formation will not occur. The low water content also means that formation of carbonic acid is limited and carbon steel can be use for the casing and liner. Where the outer casings are in contact with formation water bearing rocks, corrosion resistant 13% Chromium steel is proposed.

Similarly, conventional Portland cement degrades in the presence of CO₂, and therefore for new well construction and abandonment of existing production wells, alternative CO₂-resistant cement mixes containing non-Portland cement must be specified. Alternatively, further work may be required to investigate where non-Portland cement is/must be used to protect any Portland cement that is not in direct contact with CO₂.

The phase behaviour of carbon dioxide is the main consideration in the flow assurance engineering of the wells and injection system. The equation of state of the CO₂ has been modelled both in its as-delivered composition, and when mixed with residual methane in the reservoir. This enables the behaviour in the gaseous or the dense (liquid) phase CO₂ to be predicted at all parts of the delivery system.

A key issue is that the CO₂ remains in a controllable single phase throughout the flowing system including the wellbore during both gaseous (initially) or dense phase (after the demonstration) injection. This has been modelled using appropriate software to determine the most effective combination of pressure, temperature, and flow.

During the gaseous injection period, the bottom-hole injection pressure at the sandface and at all points upstream is limited to a maximum of about 35 bar, which ensures the CO₂ will remain a vapour and not condense in the pipeline or wellbore, even at the minimum sea temperature of 4°C. After the demonstration phase of 12 to 15 years’ CO₂ injection, the flowing system will need to be changed over to a dense phase flowing system, eventually leading to dense phase injection.

To maintain the dense liquid phase of the CO₂ in the pipeline regardless of sea temperature, the delivery pressure is set above the critical pressure for CO₂ at 79 bar. This delivery pressure is initially much higher than the reservoir pressure, however, so the CO₂ stream is throttled by a choke valve and enters the wellbore at lower pressure, to be injected in gaseous phase. The throttling is accompanied by significant heat demand due to the Joule-Thomson effect and the latent heat of vaporisation. The incoming CO₂ stream needs to be heated before the choke to prevent the temperature falling too low downstream of the expansion. This heating
represents a significant energy demand at the wellhead and must be maintained throughout the period of dense phase transport until injection also shifts to dense phase.

A check was carried out on the effects of heater failure that would cause excessive cooling of the CO₂ at the injection point: When the pipeline is in dense phase and injection is in vapour phase, a sustained heater failure could cause both formation damage and uncontrolled condensation of carbon dioxide, leading to a breakdown of stable flow in the wellbore. This would present a serious consequence of heater failure.

Abandonment of existing and new wells

Existing Hewett field wells drilled into or through the Lower Bunter have been assessed. Six exploration wells were drilled in the 1960s, of which five were abandoned and capped off below seabed; the sixth became a production well. 28 production wells are recorded, of which 6 are sidetracked wells. All these wells were designed for conventional gas extraction. E.ON’s view is that unless these wells are treated appropriately, they would be at risk of degradation of concrete and steel components where non-portland concrete or steel comes into contact with CO₂, potentially allowing CO₂ leakage to the surface. Due to these concerns over integrity, as well as because of their locations, the existing wells are considered by E.ON to be unsuitable for use as CO₂ injectors. Instead the wells will need to be capped off to a CO₂ resistant specification. There may be some opportunity for carrying out further work to overturn our view that the existing wells are unsuitable for injection purposes, but in the absence of further evidence of the suitability of existing wells and/or evidence that the risks of relying on Portland cement completions can be overlooked E.ON would prefer to use the precautionary principle. There may be some scope for incorporating the existing wells for locating instrumentation as part of the monitoring plan.

At the time of writing (2011), the Hewett field is still officially operational. None of the 28 production wells have been decommissioned. Full CO₂ resistant abandonment would comprise: pulling the production tubing, installing at least three non-Portland cement plugs, set in the caprock of the Lower Bunter and Upper Bunter reservoirs and finally just below the 30° conductor shoe, and installing appropriate monitoring. The casings need to be milled out at each plug so the seal is continuous with the caprock. This procedure is more complex and expensive than conventional hydrocarbon well abandonment using Portland cement plugs.

Difficulties will arise where the existing wells are not readily accessible. Of the production wells, six are sidetracked and have abandoned offshoots at various depths. It will be impossible to enter the original abandoned legs to replace the
cement plugs. Baker-RDS have assessed that three of the abandoned legs are sufficiently deep that the well can still be plugged to seal the Lower Bunter. Two more wells can be sealed above the Upper Bunter, although they may degrade to allow migration of CO\textsubscript{2} from the Lower Bunter to the Upper Bunter. One well remains that would be at risk of allowing CO\textsubscript{2} communication from the Lower Bunter into the Winterton Deep Saline formation at 1300ft depth. The implications of this require further appraisal.

11 of the production wells/legs continue deeper into the Zechsteinkalk and Leman formation, and may require an additional plug below the Lower Bunter to prevent downward migration of carbon dioxide and/or carbonic acid.

The biggest uncertainty surrounds the five exploration/appraisal wells. The abandonment details are not known but if normal practice was followed, they would have been plugged with Portland cement and cut off ten feet below the seabed. There is a risk that CO\textsubscript{2} could corrode and degrade the casings and plugs of these wells and leak up to the surface. They would have to be located, exposed, re-opened and a full CO\textsubscript{2} resistant abandonment carried out. Further appraisal is needed to determine whether this is even feasible and to assess the methods and costs.

The cost of the abandonment programme for the 28 production wells to CO\textsubscript{2} resistant standards has been estimated at £66.1million. This compares with an estimate for industry standard abandonment of £19.8million. The extra cost for CO\textsubscript{2} resistant abandonment is therefore £46.3million (average £1.6 million per well). This amount, however, excludes treatment of the 11 Zechsteinkalk perforations, the five exploration wells, and monitoring and mechanical protection.

From the above it is clear that any future use of the Hewett field reservoirs as CO\textsubscript{2} storage sites must be considered in the decommissioning plans agreed by the current production licence holder/operator with DECC EDU.

**Monitoring**

A monitoring programme for the CCS project is required for the lease and licence permit in line with the EU CCS directive. The purpose is to demonstrate the safety of the geological storage of CO\textsubscript{2} and confirm the integrity of the reservoir, detect any leaks or migration, adverse environmental effects and validate the computer modelling predictions.

A comprehensive monitoring scheme has been outlined, to be developed as design proceeds. As a minimum, installations at the wellhead and downhole will measure pressure, temperature, flow and CO\textsubscript{2} stream composition. Environmental monitoring will include CO\textsubscript{2} sampling at seabed, riser and platform. Seismic surveys and wireline logging can be carried out periodically to identify changes in ground
parameters. Monitoring will also be carried out at abandoned wells and will continue as appropriate from the operational phase into post-injection and long term phases.

Hazard identification and risk assessment

Hazard Identification (HAZID) is a fundamental aspect of risk management. For this project a series of workshop sessions were held to identify significant hazards at all stages of the project. The results of the HAZID study included the following two principal hazards:

1. Materials: Due to the corrosive properties of CO₂ and the potential for carbonic acid attack on cements, material selection is a key issue. Low temperatures may also affect performance of materials.

2. Existing wells: the existing wells were not designed for a CO₂ environment and were not constructed with CO₂ resistant materials or details. Furthermore, the abandoned exploration wells and redundant legs of production wells may not be feasible to access and finish to a suitable standard.

A Risk Assessment exercise was carried out on all the identified hazards and mitigation measures were proposed. A comprehensive list of further actions were identified to be addressed in later stages of design. The principal residual risks that cannot be mitigated at this stage, relate to the integrity of the existing wells.

Key Learning Points

The key learnings in relation to the well and reservoir FEED generally follow from the assimilation of established offshore technology, and the chemical processes and properties of CO₂.

- For a hydrocarbon gas reservoir identified as possibly suitable for CO₂ sequestration, an opportunity exists during decommissioning to carry out well abandonment to CO₂ resistant standards. This entails additional costs of typically £1.6M per operational well, but failure to do so could render the reservoir unviable for CO₂ storage in the future.

- Wells that have already been abandoned using conventional methods pose a risk of eventual CO₂ leakage to the surface and compromise the integrity of the CO₂ store, unless they can be located and re-plugged, which may not be feasible. In the Hewett field there are five exploration wells and three redundant legs of production wells which would require remedial works to bring them up to CO₂ resistant standards.

- Data acquisition can be difficult: ensure that all required data sets are identified and make requests as early as possible to ensure quality data is obtained.
The CO₂ equation of state and phase diagram is paramount in designing the injection process. Temperature and pressure of the CO₂ must be carefully specified to avoid uncontrolled condensation or vaporisation. To achieve the target flow rates at all stages of the injection sink development, varying levels of pre-injection heating are required to stabilise the CO₂ flowing regime.

Many standard components and materials used in the offshore industry are suitable for use in CO₂ injection applications. Particular attention must be paid to corrosion resistance and longevity in a CO₂ environment. Portland cement is particularly not recommended and alternatives are available. Use of carbon steel is only possible with a very low water, oxygen and sulphur content in the CO₂ stream.

For drilling the injection wells, the principal challenge is drilling through depleted hydrocarbon reserves at very low pore pressures, whilst minimising formation damage and debris that would inhibit the effectiveness of a well intended for injection rather than extraction.

The FEED1A study identified that further testing and analysis of core samples of the reservoir and caprock is required to confirm various chemical and engineering properties.

The links to the Technical Design – Wells & Storage documents are repeated below:

7.2. Design Philosophy - Wells Project Data
7.3. Design Philosophy - Well Drilling and Completion
7.4. Design Philosophy - Well Start up, Testing and Clean up
7.5. Design Philosophy - Storage Project Data
7.6. Storage Design and Storage Monitoring Philosophy
7.7. Establish CO₂ Supply Properties
7.8. Wellbore Stability for New Wells
7.9. Vertical Flow Performance
7.10. Injectivity - Near Well Bore Issues
7.11. Specify Initial Well Design
7.12. Specify New Well Completions Criteria
7.13. Temperature Effects on Well and Reservoir
7.14. Existing Wells Assessment
7.15. Injectivity - Refine Well Development Plan
7.16. HAZID Wells and Reservoir
7.17. Well Abandonment
7.18. Learning From Elsewhere - Literature Review
7.19. Data Management and Underpinning Subsurface Data
7.20. Validation Assessment of Reservoir
7.21. Reservoir Caprock Characterisation
7.22. Capacity Assessment – Study Effect of Formation/Dehydration Aquifers
7.23. Capacity Assessment - Determine Well Distribution Relative to Reservoir Volumes
7.24. Assessment of Natural Integrity
7.25. Full Overburden Mobility Modelling
7.26. Assessment of Engineered Integrity
7.27. Risk Assessment and Mitigation
7.28. Design Monitoring Programme for Well and Storage Assurance
8. Health and Safety

8.1 Commentary

Safety Management In Design and Inherently Safer Design (ISD) are the processes which ensure hazards have been designed out of a process (ISD) or a facility, and where this is unachievable, mitigated.

These processes rely on designers:

- Applying knowledge and experience to the process design (ISD) and facilities design;
- Considering maintainability and constructability in process design to minimise inventories of hazardous materials;
- Substituting hazardous materials for less hazardous ones;
- Reviewing the process flow to ensure that hazardous intermediates are avoided; and
- Making equipment failsafe if possible e.g., a pipeline system could be designed for the maximum possible pressure it could physically be exposed to, removing the need for relief systems, pressure control loops and operator intervention – all of which can fail.

Guidance on ISD and Safety Management in Design has been issued to all E.ON and Contract staff involved in the project (an example of which is shown in the table below) to ensure that these design practices are built in to the project.

<table>
<thead>
<tr>
<th><strong>Guide Word</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimise</strong></td>
<td>Use of smaller quantities of hazardous materials when the use of such materials cannot be avoided;</td>
</tr>
<tr>
<td></td>
<td>Perform a hazardous procedure as few times as possible IF the procedure is UNAVOIDABLE.</td>
</tr>
<tr>
<td><strong>Substitute</strong></td>
<td>Replace a substance with a less hazardous material;</td>
</tr>
<tr>
<td></td>
<td>Replace a processing route with one which does not involve hazardous materials.</td>
</tr>
<tr>
<td><strong>Attenuate</strong></td>
<td>Use hazardous materials in their least hazardous form or identify processing options that involve less severe processing conditions (lower temperatures, pressures etc.)</td>
</tr>
<tr>
<td>(moderate)</td>
<td></td>
</tr>
<tr>
<td><strong>Simplify</strong></td>
<td>Design processes, processing equipment and procedures to eliminate opportunities for errors by eliminating use of add-on (engineered) safety features and protective devices.</td>
</tr>
</tbody>
</table>
For this early FEED 1A stage, preliminary hazard analysis for the design of the plant, pipeline and platform has been performed by a number of combined HAZID (Hazard Identification) and ENVID (Environmental Hazard Identification) studies. HAZID/ENVID studies were carried out for the following sections of the project:

- Kingsnorth Power Plant (impact on and from CCS);
- Kingsnorth CO2 capture and compression plant;
- CO2 Pipeline (On and Offshore);
- Kingsnorth CO2 Injection Platform;
- Wells and Reservoirs.

The results of the HAZID studies for the power plant and capture and compression plant are recorded in the ‘HAZID Report’ and ‘HAZID Report Addendum’ in this Chapter. The pipeline and platform HAZID is in Chapter 6 and the wells and reservoirs HAZID in Chapter 7.

The teams which supported these studies were drawn from the appropriate design contractors, with other E.ON and external safety and environmental specialists included as required. HAZID/ENVID items were transferred into a Safety Risk List file and reviewed. Upon review by various working groups and the designers a decision was then made for each issue identified as to which items would be risk assessed during FEED 1A (current), and which would be deferred until later project stages for risk ranking; this decision was based on whether or not sufficient information was available during FEED 1A for a reasonable risk assessment to be made. The Safety Risk List will be carried forward into subsequent stages of design and engineering to inform the design teams.

Other reviews, such as SIMOPS (Simultaneous Operations) studies have been carried out. A review of Major Accident Hazards for the pipeline has been undertaken and the outcome is described in the report ‘ALARP Review Report for Genesis Scope of Work’. As the project develops, further detailed hazard analysis (e.g., HAZOP, LOPA etc), will be carried out as the level of design detail allows.

Design Risk Assessments were carried out by the relevant design teams, with support from the Safety Consultant where appropriate. DRA’s were qualitative rather than quantitative, due to the early stage of design within FEED 1A. The Design Risk Assessments are collated and summarised in the ‘CDM Design Risk Register’.

A draft Pre-Construction Safety Report (as required under the COMAH regulations) has been produced to further inform the design process, and enhance our understanding of the significant hazards, both safety and environmental, associated with these processes.
This overall approach to Health and Safety is set out in more detail in the ‘Health and Safety Design Philosophy’.

**Operational Safety Working Group (OSWG)**

The OSWG was established early in the project to facilitate review and discussion of design and engineering reports from a safety context. This group contained colleagues from across E.ON and relevant contractors, as well as third-party specialists and met regularly through the FEED programme. The forum provided an opportunity to ensure that safety management professionals from many contributors were given an opportunity to comment on all the main deliverables that had a safety management context and introduce new perspectives to the content of each deliverable. Additionally the OSWG forum was able to identify a number of issues to be added to the safety risk list for further consideration in risk assessments either during the term of FEED 1A or in any future design activity. The safety risk list, maintained by the safety (in design) manager from the combined results of HAZID workshops and the meetings of the OSWG group provided a very comprehensive checklist of safety in design issues that were being considered by individual designers and/or should have been considered by individual designers. The list proved useful for checking that issues that needed to be risk assessed at the FEED 1A design stage (conceptual design) were in fact being risk assessed by the individual designers and in making sure that the appropriate risk assessments were being entered into the CDM Design Risk Register. A report on the work of this group is included in Chapter 4.

**Carbon Dioxide Hazards**

E.ON has recognised the potential dangers from CO₂ from the onset of the project and has collaborated with external groups such as the CCSA (Carbon Capture and Storage Association) for a number of years and developed its own in-house CO₂ modelling capability. E.ON has also utilised input from other organisations with experience in CCS, including MMI Engineering Ltd, who have provided safety engineering consultancy services to the project.

The Health and Safety Executive publish data to set limits for worker exposure to a large number of substances. These Worker Exposure Limits are set at two levels – one is for the maximum time-weighted average exposure over a normal working day of eight hours (the Long Term Exposure Limit), the other is the maximum time-weighted average exposure level over a fifteen minute period (the Short Term Exposure Limit, or STEL). These are generally expressed as the concentration of the hazardous substance in air. The Health and Safety Executive publish this data in a document titled EH40 and a comparison of these levels for some substances is shown below:
<table>
<thead>
<tr>
<th>Substance</th>
<th>Long Term Exposure Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg.m(^{-3})</td>
</tr>
<tr>
<td>Hydrogen Cyanide</td>
<td>None</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>35</td>
</tr>
<tr>
<td>Liquefied Petroleum Gas (LPG)</td>
<td>1,750</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>9,150</td>
</tr>
<tr>
<td></td>
<td>Short Term Exposure Limit</td>
</tr>
<tr>
<td></td>
<td>mg.m(^{-3})</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>232</td>
</tr>
<tr>
<td></td>
<td>2,180</td>
</tr>
<tr>
<td></td>
<td>27,400</td>
</tr>
</tbody>
</table>

From the table it can be seen that the hazardous impact of CO\(_2\) only occurs at very high levels of exposure when compared to some other commonly known hazardous substances.

CO\(_2\) is a gas naturally present in the atmosphere, and it has an essential role in our respiratory process. The air we breathe in contains about 0.04% CO\(_2\), but the air we breathe out can contain up to about 4% CO\(_2\). Increases in the atmospheric level of CO\(_2\) that we breathe in can have significant effects, even at levels below that which we normally breathe out.

Carbon dioxide has two key physiological effects: it acts as an asphyxiant and also has toxicological effects. At concentrations of 1.5% carbon dioxide humans are likely to suffer symptoms such as headaches, tiredness and increased breathing. At 6.5% increase in carbon dioxide concentration can induce visual impairment and/or loss of consciousness. Above 10% loss of consciousness can occur so rapidly that the person is unable to save themselves. Prolonged exposure to high concentrations may eventually result in death from asphyxiation.

When looking at the potential risks around carbon dioxide capture, storage and transport, the term toxic has been used widely in the various reports and philosophies relevant to the project when describing the risk levels to draw attention to these levels of exposure and their consequences.

Although CO\(_2\) is not classified as a dangerous substance, E.ON has treated it as such for Major Accident Hazard purposes.

**Dispersion Modelling**

Initial dispersion modelling has been undertaken using PHAST and E.ON ENT CO\(_2\) adapted CFD (Ansys) software. This initial modelling has been based on data provided by the Health and Safety Executive on the airborne concentrations and duration of exposure which would produce particular levels of toxicity. Future
modelling will also look at the long term exposure limit and the short term exposure limit levels for CO2. Pipeline routing has been based on achieving the maximum practical distance from occupied buildings. CO2 modelling is also looking into the low temperatures generated by CO2 releases in order to determine the potential adverse impact on structures and other plant items. This is described in detail in the ‘Dispersion Modelling Strategy’ and in the ‘Consequence Assessment of CO2 Pipeline Releases’.

E.ON is supporting the CO2PIPETRANS Joint Industry Project via E.ON Ruhrgas, and input from this (and others), will be utilised in the future development of the project.

**Noise Protection**

Noise levels in the workplace and the environment are a significant health issue throughout the construction period and the operational life of the project. The approach to control of noise is described in the ‘Full System Noise Protection Philosophy’.

The links to the Health & Safety documents are repeated below:

8.2. **HSEQ Full System Noise Protection Philosophy**
8.3. **Dispersion Modelling Strategy**
8.4. **ALARP Review Report for Genesis Scope of Work**
8.5. **CDM Design Risk Register**
8.6. **HAZID Report**
8.7. **HAZID Report – Addendum**
8.8. **Consequence Assessment of CO\textsubscript{2} Pipeline Releases**
8.9. **Health and Safety Design Philosophy**
9. Environment and Consents

9.1 Commentary

Overview

One of the key objectives of the FEED 1A study was to develop information across the project chain, from CO$_2$ generation to storage in sufficient detail to enable production of applications for environmental consents. To achieve this objective, relevant consents needed to be identified and discussions with regulatory authorities were held to understand what was required from whom and when.\textsuperscript{1} This information was then used to advise the project team of the required level of detail needed, both from a plant/process aspect and an environmental studies perspective. A Consents Philosophy was generated upon commencement of the FEED 1A to develop a programme of work to achieve this objective, and identified the following groups of consents:

i) Power and capture plant: 1989 Electricity Act – Section 36

An application for Section 36 Consent was submitted to the (then) Department of Trade and Industry in 2006 for development of Kingsnorth Units 5 and 6. Whilst some of the original documentation from 2006 remained current, significant additional work was required to update the Environmental Statement (ES). The additional work included new data relating to the capture plant, the tie into the CO$_2$ transport pipeline and improvements to the main plant layout and design.

ii) Onshore pipeline: 1990 Town and Country Planning Act

Upon project commencement it was unclear whether the pipeline would require consent from the Infrastructure Planning Commission (IPC) under the 2008 Electricity Act. Discussions with DECC and the IPC concluded that the onshore pipeline planning application should be submitted to Medway Council under the Town and Country Planning Act 1990 as it was less than 10 miles in length. A separate application for the offshore pipeline should be submitted to DECC’s Energy Development Unit - Offshore Environment and Decommissioning Unit (EDU-OED). On this basis an ES was prepared for the onshore pipeline by specialist consultants,

\textsuperscript{1} In this chapter summary, DECC refers to the regulatory arm of the Department of Energy & Climate Change.
RSK, extending from the boundary of the proposed new power station to the low water mark within the Thames Estuary.

iii) Offshore Pipeline

An ES was also prepared by RSK for the ~265km offshore section of the pipeline, from the high water spring tide line to a tie-in point at the Hewett Field. Discussions with DECC EDU-EMT (Environmental Management Team) concluded that whilst the main application and technical assessment would be made by DECC, the Marine Management Organisation (MMO) is the named competent authority for the part of the pipeline from the high tide mark to the Thames Bay Closure Line. A license from the MMO is required under the Marine and Coastal Access Act 2009. E.ON considered the prospect of providing separate applications to each regulator, it was considered more pragmatic by all parties to develop a single ES for the entire offshore route, for assessment by both authorities and ensure a joined up process.

iv) Offshore platform

A separate application to DECC is required for the offshore platform, located on the Hewett Field, approximately 25km north east of Bacton on the Norfolk coast. There was insufficient information about the exact location and design of the platform to enable preparation and submission of the platform ES within FEED 1A. Due to the constrained timescales within the CCS Demonstration Competition process there was insufficient time to complete this process, especially as the application may require exploratory drilling to fully understand the environmental impact of the platform and this was not possible without first knowing the location. Consequently, the environmental studies associated with the platform could not be undertaken during FEED1A of the project, and this element of consenting activity is to be undertaken during subsequent stages of the project.

v) Storage consents

Consents for storing CO2 are required from DECC and The Crown Estates. The application process for these consents, and the information required for each application, was being consulted upon at the start of FEED 1A, and continues to develop, assisted by regulations laid before Parliament in September 2010. The work undertaken during FEED 1A identifies the likely requirements for each consent application and the relevant timescales involved, which will be used for subsequent storage consenting work for the project.

The scope of the environmental work undertaken during FEED 1A was developed from two perspectives. In addition to providing sufficient environmental information for consent applications, it was also necessary to follow standard E.ON procedures and guidance on assessing and managing environmental risks. The latter
requirements are detailed in the Environmental Philosophy, included in this chapter, which refers to the systematic identification of hazards, compliance with regulatory requirements and adoption of best available techniques (BAT) for preventing or minimising environmental impacts. These requirements were addressed through the hazard studies described in Section 8 and the environmental impact assessments presented in this Section of the report. Environmental considerations will continue to be considered in subsequent design phases of the project.

The following sections summarise the key issues arising from preparation of each of the consent applications detailed above.

**Power and capture plant: 1989 Electricity Act – Section 36**

The original ES for Kingsnorth Units 5 and 6, submitted in 2006 with updated information in 2007, required further updating to include the CO₂ capture plant, the on-site section of the transport pipeline and to reflect current UK guidance. Discussions were held with a large range of consultees on these proposed amendments, including DECC, Medway Council, Natural England and the Environment Agency. To minimise the additional work required by consultees, it was decided that, rather than submit additional information as a separate document, a consolidated ES would be prepared, based on the same structure as the original submitted in 2006, to include information already submitted since the original application and the additional information associated with the capture plant. DECC advised that the consolidated documents should be submitted to them and sent to statutory consultees for comment, with further consideration being required by Medway Council’s planning committee.

Although much of the original information submitted in 2006 remains valid, the consolidation of the content of these documents to reflect subsequent submissions and additional information required substantial editing. The additional information primarily revolved around the CO₂ capture plant, designed to remove CO₂ from emissions associated with 300MWₑ net export, and the on-site section of the CO₂ transfer pipeline. Both the construction profile and environmental emissions were re-evaluated to include capture plant requirements, and the cumulative impacts associated with both the new Kingsnorth and the proposed Damhead Creek II power plant, situated to the north of the proposed Kingsnorth site, were also considered. The key issues associated with the capture plant and presented in the integrated power/capture plant ES are provided below:
i) Policy context. Since submission of the original application in 2006, DECC published its policy regarding the development of new coal plants, requiring the capture and storage of CO₂ from at least 300MWₑ net export. The additional information in the consolidated ES included a description of the need for the capture plant, identifying the reduction in CO₂ emissions of over 4 million tones, compared to existing unabated plant operating at around 35% efficiency.

ii) Transport. The build program for the integrated power/capture plant is expected to last for 48 months. The capture plant does not affect the peak number of vehicle movements and workers on-site, as its construction will be scheduled to avoid the Unit 5 and 6 construction peak.

iii) Landscape and Visual. The capture plant will introduce some large plant items which may impact upon the local landscape. The most significant plant item will be the 75m high absorption column, in which CO₂ is removed from the flue gas by the solvent. The flue gas quencher and the solvent regeneration column will be around 55m in height. The visual impact of these plant items will be limited due to being located to the south of the taller boiler plant. The plant is also in keeping with the current industrial landscape, hence the overall impact is considered low.

iv) Air Quality. The new plant would be fitted with flue gas desulphurisation (FGD), selective catalytic reduction (SCR) and electrostatic precipitators (ESP) to enable compliance with new emissions standards and all relevant air quality standards for acid gases, oxides of nitrogen and particulates, respectively. As well as removing 90% of CO₂ from the treated flue gas, the carbon capture plant will also reduce emissions of acid gases and nitrous oxides.

v) Water Quality. The major aqueous discharge from the plant is cooling water. The current plant can abstract and discharge up to 65m³ per second. The new units, without the capture plant, would discharge around 53m³ per second. The proposed carbon capture plant also requires some cooling demand, hence the overall cooling requirement for Unit 5 fitted with carbon capture is around 30m³ per second, giving a total requirement for both units of 56m³ per second. The impact of this release on the Medway Estuary, a European-designated site for ecological protection, was modelled and demonstrated that the thermal plume would comply with guidance issued by the Environment Agency. Water quality impacts were also modelled and demonstrated that impacts would not be significant.

vi) Noise. The new Kingsnorth Units 5 and 6 will generate less noise than the existing site. However, the introduction of the capture plant will increase noise emissions, particularly as a result of CO₂ compression prior to export through the pipeline. A number of design scenarios for the compressors were considered and concluded that, depending on the supplier of the equipment and the level of
abatement adopted, there is potential for deterioration of the existing noise climate. Further evaluation of this impact and the required abatement is necessary, once detailed information on the specific plant item is available.

vii) Waste Generation. Typical wastes arising from the power plant include ashes, used oils, maintenance wastes and sludges. The capture plant introduces a further waste stream, comprising a sludge from the solvent reclaiming process, containing Heat Stable Salts (HSS), amine solvent and associated degradation products. This sludge is likely to be classified as hazardous waste due to the high amine content, but further work is required to conclusively demonstrate this. It is a relatively small waste stream, with around 900 tonnes per year being generated. There are various management options for this waste stream, which require further consideration. For the purposes of the ES it was assumed that the sludge would be managed off-site by a suitably licensed contractor.

The consolidated ES has been produced to reflect the integrated power/capture plant design. It was produced following discussions with key consultees, and reflects current environmental modelling and impact assessment standards. The overall conclusion from the assessment is that CO₂ emissions from the power plant would be significantly lower than the existing plant due to greater plant efficiency and capture of CO₂ from emissions associated with 300 MWe net export. Environmental impacts associated with the capture plant include additional cooling water demand, noise emissions and emissions to air. However all of these impacts can be managed and will remain within acceptable standards through a combination of process design and mitigation.

Onshore pipeline: Town and Country Planning Act 1990

The onshore pipeline ES was developed following discussions with a range of statutory and non-statutory consultees, supported by public exhibitions and consultation on an ES scoping document. Collectively this approach ensured that all of the key planning considerations were identified from the outset and could be incorporated into the final documents.

Initially a range of possible onshore pipeline routes from the power plant to the Thames Estuary were identified. A series of workshops were held to consider the relative impacts of each route in terms of safety, environmental and technical feasibility. The outcome was selection of the northerly route, which was the shortest, had the least housing in the near vicinity and, by avoiding the marshes in the Stoke/Allhallows area, posed the fewest environmental and technical feasibility issues.
The ES provides an assessment of the impacts of construction and operation of a continuously welded steel 36” outside diameter pipeline, approximately 11km in length, running from the power station to the low water mark in the Thames Estuary. The pipeline would be buried for its entire length to a depth of at least 1.1m to the top of the pipeline. An onshore Above Ground Installation (AGI) would be installed near the coast to enable pipeline isolation for maintenance or in the unlikely event of an emergency.

A 1km pipeline corridor from the site to the coast was initially selected for detailed consideration. Two potential beachfall locations were also considered, located at St. Mary’s Marshes and Dagnam Saltings, to the east. During the course of the FEED 1A program environmental studies on a range of issues, including ecology, landscape, noise and land quality, were undertaken, enabling identification of a preferred pipeline route. The ES presents a pipeline corridor width of 100m, which allows for minor deviations in exact route and a working area during construction. The St Mary’s Marshes location was identified as the preferred beachfall location due to lower landscape and visual impacts.

Development of the ES for CO₂ transport pipeline encountered typical issues for all onshore pipelines, such as proximity to human and environmental sensitivities, crossing of transport infrastructure, watercourses and drains, construction impacts and landscape and visual disturbance. Specific issues relating to transport of CO₂ were primarily raised and addressed through discussions with consultees and at exhibitions.

Offshore Pipeline

The ES for the offshore pipeline covered the route from St. Mary’s Marshes to the Hewett Field in the North Sea. The total offshore length of the pipeline is approximately 265km. Extensive consultation with relevant parties has taken place to obtain necessary data for the ES. In addition, an offshore survey of the pipeline route was undertaken to provide specific information along the proposed route for inclusion within the ES.

The Environmental Impact Assessment for the offshore pipeline can be considered in three sections, comprising the intertidal, the shallow near-shore subtidal and the deeper offshore subtidal. The intertidal section of the pipeline route is approximately 3km in length and extends across the mudflats from St. Mary’s Marshes to the low water mark in the Thames Estuary. The pipeline would be trenched across the mudflat and installation would involve pulling the pipeline from onshore into the trench using a wire from a barge anchored offshore. Following installation the trench
would be back-filled with gravel to a depth of one metre below the natural seabed level. The final metre would be left fill naturally.

The Thames Estuary is relatively shallow and is a heavily used shipping route. Consequently the second section of the pipeline, extending 45km east into the North Sea, would be buried to minimize the potential for collision. A trench would need to be dug into which the welded pipeline would be laid using an offshore lay-barge. This would cause significant local ecological disturbance, hence laying would be timed to avoid critical seasonal impacts associated with overwintering, spawning or migration.

The third and longest section of the pipeline extends north to the Hewett Field. Both near-shore and offshore options for the pipeline were considered. The near-shore option would involve routing around more shipwrecks and would cross shipping lanes into many ports along the east coast. It would also require smaller pipe laying vessels than the offshore-option, reducing the rate at which the pipeline could be constructed to just 1-3 kilometres a day, compared with the 6 kilometres a day which could be achieved by larger vessels operating in deeper water. Faster pipe laying helps reduce any impact on shipping and other maritime operations. Consequently it was concluded that the offshore route, laying in typical depths of 20-40m, was the better option and would have a lower environmental impact.

The offshore section of the pipeline would be laid on the seabed. This may require some infilling of troughs or cutting of sandwaves to ensure that the pipeline is always in contact with the seabed. Any reduction in sandwave peak is anticipated to last only a matter of months before sediment is deposited, returning the waves to their natural height.

As for the onshore section of the pipeline, the issues encountered during preparation of the ES were generally typical of those encountered for any large pipeline construction. The one area that does differ slightly relates to the angle of the bend of the pipeline across the intertidal mudflats into the Thames Estuary. The flexibility of the pipeline is limited by the requirement for a pipewall thickness of one inch, thus increasing the arc of the pipeline and the overall impact on the intertidal area.

**Offshore platform**

There was some consideration with DECC as to whether the ES for the offshore pipeline could include the area of the offshore platform location as well. Whilst this may have been desirable, it was not possible to do this as the exact location of the CO₂ wells, and thus the platform itself, was not known. Some offshore survey work of the storage reservoir and the local environmental conditions is likely to be required.
to inform the ES, and this is scheduled for subsequent stages of the Kingsnorth CCS project.

Storage consents

The Hewett Field is located around 25km off the north Norfolk coast and has an average water depth of around 35m. The project would store up to 20 million tonnes of CO₂ in the Lower Bunter sandstone formation, approximately 1300m below sea level.

Various consents are required for storage of CO₂, and need to be obtained from DECC and the Crown Estates to ensure that appropriate considerations regarding environmental and leasing arrangements have been taken into account. The overall process can be broadly divided into five stages, covering the project lifecycle, from initial exploratory drilling, through to closure and transfer of responsibility back to government. The initial stages of exploration and drilling may not be required if sufficient data are already available to understand how the site will be used and managed.

A CO₂ storage licence from DECC would provide exclusivity for carbon storage activities during the appraisal, operational and closure periods of the project. However, this would include a time-limit within which an application to DECC for a storage permit must be made. The storage licence application comprises a detailed evaluation of the project, including information on the overall project development plan, the size and location of the proposed storage site, physical and chemical properties of the site and how they will change over time, well design and construction, risk management and monitoring and reporting plans. The storage permit application would provide information obtained from the exploratory phases and the permit must be obtained prior to commencement of the operational phase.

Concurrently with the application for a storage license from DECC, an application for a lease for storage must also be obtained from The Crown Estates (TCE). DECC and TCE have committed to processing these applications in parallel to facilitate development of storage facilities. The current intention is that a lease would be provided reflecting the site applied for in the licence application, and this would be subsequently modified prior to storage, to reflect the site dimensions and characteristics provided in the permit application.

The CO₂ storage consents process has been extensively developed by DECC during the FEED 1A period and this has enabled development of outline framework application documents for this project. However further work is required, particularly with respect to the site-specific considerations for the Hewett Field and the
associated timings of applications, before applications can be fully developed for submission.

Conclusions

There were significant uncertainties at the outset of the project regarding the types of consent required. This was a consequence of the planning consent for Kingsnorth Units 5 and 6 having already been submitted in 2006, new government policy and draft regulatory guidance, and ongoing government consultations on regulatory issues. Many of these issues were resolved, enabling development of consent applications for the integrated power and capture plant and onshore and offshore CO₂ pipeline. However in some cases, particularly for the offshore platform and storage, uncertainty remained throughout the project. In these instances the deliverable was an interpretation of the regulatory requirements that will need to be reviewed and taken into account to obtain consents during subsequent stages of the project.

The links to the Environment and Consents documents are repeated below:

9.2. Consent Philosophy
9.3. Environmental Philosophy
9.4. Kingsnorth Environmental Statement
9.4.1. Kingsnorth Environmental Statement Figures.pdf
9.5. Kingsnorth EP Application Form
9.6. Onshore Pipeline Scoping
9.7. Complete Onshore Pipeline Environmental Statement
9.8. Onshore Pipeline ES Non Technical Summary
9.9. Offshore Pipeline Scoping
9.10. Offshore Pipeline Environmental Statement
9.11. Offshore Pipeline ES Non Technical Summary
9.12. Pipeline Scoping Document Comments
9.13. Genesis Offshore Environmental Plan
9.15. Environmental Commitments Compliance Register
9.16. Emissions From Offshore Construction Activities
9.17. Noise Model and Report for Offshore Pipeline, Platform and Well Drilling
9.18. Waste Management Plan
9.19. Define Lease Licence Permit Submission Requirements
9.20. Storage Lease application
9.22. Consenting Register
10. Project Management Reports

10.1 Commentary

This chapter contains the output from many of the Project Management processes which control and report the progress of the FEED. The following commentary gives the reader a brief guide to the project management process or approach which has been used.

FEED Programme

In order to scope out, control and report the FEED activity, a Work Breakdown Structure was developed. This structure had the following hierarchy –

Level 1 – Chain Element
Level 2 – Phase
Level 3 – Discipline
Level 4 – Work Package (including Cost Time Resource ‘CTR’ definition)

The chain elements of the FEED were defined by the physical elements of the proposed project, plus the overarching management activities, as set out in the table below:

<table>
<thead>
<tr>
<th>Chain Element</th>
<th>1.0 Integration</th>
<th>2.0 Power plant</th>
<th>3.0 CO2 Capture</th>
<th>4.0 CO2 Transport Conditioning</th>
<th>5.0 CO2 Transport</th>
<th>6.0 Injection Conditioning</th>
<th>7.0 Well design</th>
<th>8.0 Storage Design and Monitoring</th>
<th>9.0 HSE and Quality</th>
<th>10.0 Commercial</th>
<th>11.0 Consenting</th>
<th>12.0 Management</th>
</tr>
</thead>
</table>

Once the outline structure of the FEED 1A activity developed, the design scope and deliverables were established and defined using CTRs. These CTRs were then used to obtain budget quotes from the project participants. The CTRs were then appraised and prioritised and used to develop the FEED 1A programme of work. This programme was initially developed by the project participants for their individual scope of work, and then pulled together into a single Integrated Master Schedule (IMS).
The programme is in the form of a fully resource loaded, logically linked network diagram, presented as a Gantt chart with the following fields clearly identified:

- Activity ID;
- Description;
- Original Duration;
- Remaining Duration;
- Early/ Actual Start;
- Early/ Actual Finish;
- Percent Complete;
- Total Float;
- Variance (Finish v Baseline Finish).

Each participant (Contractor) was responsible for updating their elements of the Integrated Master Schedule, with appropriate review and challenge from E.ON.

**Reporting**

E.ON reported project progress monthly back to the Authority during the FEED period via two key mechanisms:

- Monthly Management Report;
- Quarterly Gateway Review Report;

Both progress reports were identical in content, however the Gateway reports reflected the contract review points. The reports were in a dashboard style and highlighted key issues and covered the following topics: -

- **Summary** - a high level overview of progress made, issues, highlights and next steps.
- **Programme Summary** - a graph of three performance S-curves of progress against time (original baseline, actual and earned value), with commentary.
- **Programme by WBS** - similar S-curve graphs for each ‘Chain Element’ within the project.
- **Deliverables** – a schedule listing by WBS the progress of deliverable production. A more detailed Deliverables Register is contained within the Appendix.
• **Qualitative Risk** - A risk dashboard and commentary on the key mitigation activities carried out. The top 50 project risk register is included in the appendix.

• **Quantitative Risk** - (GR4 Report only). Detail the crucial confidence results for the cost and schedule QRA.

• **Consent register** – a progress update on key consenting areas.

• **Appendices** - includes a CTR register, a deliverable register, decision register and Health and Safety dashboard.

**Labour Costs and other FEED Costs**

A summary of the FEED outturn manhours is included in section 10.1.7. These hours have been rolled up to a discipline (programme level 3) level within each of the chain elements, and show the total manhours utilised within each FEED month.

In addition, a list of all FEED CTR outturn costs is included. The costs have been broken down into labour and non-labour costs, and have been further split to show the cost incurred by month.

**FEED Cost Summary**

The table below gives a summary of the labour and non-labour cost elements of the project. Approximately 72% of the cost was directly attributable to labour costs. Of the remaining 28% non-labour cost, the single largest contribution was the offshore pipeline survey, accounting for approximately 16% of the total project cost.

<table>
<thead>
<tr>
<th>PROJECT COST SUMMARY (by WBS)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>all figures are costs in Pounds (£)</td>
<td>Labour</td>
</tr>
<tr>
<td>TOTAL</td>
<td>8077362</td>
</tr>
<tr>
<td>1 Cross System Integration</td>
<td>1310261</td>
</tr>
<tr>
<td>2 Power Plant</td>
<td>461907</td>
</tr>
<tr>
<td>3 CO2 Capture</td>
<td>588156</td>
</tr>
<tr>
<td>4 CO2 Transport Conditioning</td>
<td>181032</td>
</tr>
<tr>
<td>5 CO2 Transport</td>
<td>536501</td>
</tr>
<tr>
<td>6 Injection Conditioning and Offshore Infrastructure</td>
<td>366691</td>
</tr>
<tr>
<td>7 Well Design</td>
<td>397234</td>
</tr>
</tbody>
</table>
### PROJECT COST SUMMARY (by WBS)

<table>
<thead>
<tr>
<th></th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labour</td>
</tr>
<tr>
<td>8 Storage Design and Monitoring</td>
<td>544376</td>
</tr>
<tr>
<td>9 Health, Safety and Quality</td>
<td>340922</td>
</tr>
<tr>
<td>10 Procurement and Commercial</td>
<td>217172</td>
</tr>
<tr>
<td>11 Consenting</td>
<td>792453</td>
</tr>
<tr>
<td>12 Management</td>
<td>2298030</td>
</tr>
<tr>
<td>13 Knowledge Transfer</td>
<td>42629</td>
</tr>
</tbody>
</table>

### Project Decision Register

Project Decisions were recorded, controlled and communicated via the Decision Register, for decisions which were deemed significant enough for management approval. Responsibility and a required by date were included to ensure awareness for the entire project team.

The following tables set out the levels of responsibility for managing the Decision Register process, and relates to the levels identified in the decision register.

<table>
<thead>
<tr>
<th>DECISION LEVEL</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROJECT PARTICIPANT</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>SINGLE POINT OF CONTACT (SPOC)</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>TECHNICAL PROJECT MANAGER</td>
<td>C</td>
<td>C</td>
<td>A</td>
<td>I</td>
</tr>
<tr>
<td>COMMERCIAL PROJECT MANAGER</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>I</td>
</tr>
<tr>
<td>GENERAL PROJECT MANAGER</td>
<td>A</td>
<td>A</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>MANAGING DIRECTOR</td>
<td>A</td>
<td>I/-*</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* GPM will use judgement to determine if type II decision requires Managing Director to be informed.

### Key

- A = Approve
- C = Consult
- E = Execute
- I = Inform

**Type I decision**
Decision is of significant project importance (i.e. a complete change of project direction or scope) and requires approval from either the General Project Manager and/or the Project Director.

**Type II decision**
Decision is of sufficient project importance (i.e. key design decisions...
that impacts more than one WBS) and requires approval from the General Project Manager and/or the Commercial Project Manager.

Type III decision
Decision is of moderate project importance (i.e. considerable design changes within a WBS) and requires approval from the Commercial Project Manager and/or the relevant Technical Project Manager.

Type IV decision
Decision is of minor project importance (i.e. day to day design decisions) and requires approval from the responsible SPOC, while keeping senior project member informed.

Risk Management System
Throughout this FEED the management of risk was a key activity. This has helped inform and better understand the important risks faced by the project. This “first of a kind” project saw a large number of new risks being identified, assessed, controlled and monitored during FEED. A crucial component was the identification of additional work to be carried out in future project stages.

The project evolution can visibly be seen by comparing the GR1 Risk Register and the GR4 Risk Register included within this Chapter. Key areas detailed within the risk register’s included pre-mitigated risk scores, current risk scores, risk movement indicators and whether the risk could hinder the project proceeding or not. The comparison of each register demonstrates that the project has an improved understanding of the risks of the CCS project development.

Quantitative Risk Analysis
The risks identified and assessed by the project formed the basis of the Quantitative Risk Analysis. The key cost and schedule risks were modeled using specific software (@risk – cost, primavera risk analysis – schedule) that in turn modeled possible cost overrun or schedule delay faced by the project. A significant theme from both the cost and schedule QRAs is that the project still has large uncertainties, particularly in relation to quantifying future cost and expected activity durations. It is anticipated that these uncertainties will be reduced to acceptable levels in future development stages.

Level 2 Programme
The Level 2 project programme is presented in the form of a Critical Path Method (CPM) Gantt chart. This demonstrates the logical sequencing and timing of principal activities and tasks required to achieve Carbon Capture and Storage and the integration between the Power Plant and the CCS chain. The programme summarises the timeframes, milestones and dependencies for the ‘Chain Elements’
of power plant, carbon capture and compression, transport, injection and storage for each principal phase.

The critical path is determined by the logical sequence of events required to discharge the various permitting and consent conditions deemed necessary to achieve an investment decision. Once the Authority confirms the intention to invest, this critical path is driven by the engineering, procurement and construction of the base plant which in turn drives a system based commissioning schedule through the CCS chain.

An initial Level 2 programme was established at the beginning of FEED 1A. This was assessed and fundamentally updated taking into account the additional knowledge gained during FEED 1A. Both versions of this programme are included in this section.

**FEED 1A Project Cost Estimates**

An estimating philosophy was established in FEED to set the standards for the estimates produced from across the project participants, including:

- To ensure a consistent approach in the collection, calculation and presentation of costs across all FEED Participants;
- To ensure that all likely project costs are identified and captured along with all associated details.

A standard template was established for each participant to complete with the details of their section (i.e. Chain Element) of the cost estimate.

The cost estimate was broadly consistent with Class 3/4 estimate as defined by AACE.

**Stakeholder Management**

In recognition of the importance of many stakeholders to the success of the project, E.ON has a collaborative stakeholder management strategy, designed to:

- Build relationships with key influential organisations and individuals, recognising stakeholder needs, concerns, and relationships;
- Establish expectations for the scope of the project and target channels for influencing, building allies and aligning objectives;
- Establish effective stakeholder engagement, through an extensive communication plan;
E.ON believes that stakeholder communication is crucial from the planning stage, through development and construction, to commissioning and operation, although the level of involvement by different stakeholders is likely to change during these stages.

The links to the Project Management documents are repeated below:

10.2. FEED Programme - Pre-FEED
10.3. FEED Programme - Post-FEED
10.4. Monthly Reports and Gateway Review Reports
10.5. Decision Register
10.6. Risk Register (Gateway Review 1 - May 2010)
10.7. Risk Register (Gateway Review 4 - March 2011)
10.8. Quantitative Risk Analysis Report
10.9. Labour Costs and other FEED Costs
10.10. Level 2 Project Programme – Pre-FEED
10.11. Level 2 Project Programme – Post-FEED
10.13. Pre-FEED Project Cost Estimates
10.15. Economic and Commercial Definitions Philosophy
10.16. Evidence of Local Stakeholder Management