

- 6 JAN 2015

Mr A Leakey
PPC Compliance Team
Natural Resources Wales
Rivers House
St Mellons
Cardiff
CF3 0EY

Your ref
Our ref RP3133LD
Name Amy Lavisher
Phone 01446 752270
Fax 01446 750844
E-Mail amy.lavisher@rwe.com

18th December 2014

Dear Mr Leakey

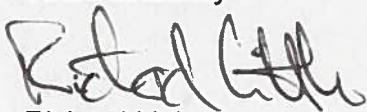
**RWE Generation UK plc, Aberthaw Power Station, Environmental Permit
RP3133LD**

RE: Improvement Condition 26-28

With reference to the above Improvement Condition please find enclosed the "Commissioning, Operation & Performance Report for the Carbon Capture Pilot Plant". The report summarises the commissioning and operational activities of the carbon capture pilot plant during the demonstration period. It includes a review of commissioning against the commissioning plan specified in pre-operational measure PM6 and a review of the environmental performance against the emissions monitoring protocol specified in pre-operational measure PM7. The report evaluates the emissions of residual amines and their reaction products, including nitrosamines and summarises learning points for future applications of carbon capture technology on combustion plant for power generation.

Please contact Amy Lavisher on the above telephone number if you have any questions or if clarification is required.

Yours sincerely



Richard Little
Station Manager

Enc:

RWE Generation UK plc, November 2014, "Commissioning, Operation & Performance Report for the Carbon Capture Pilot Plant", Ref. RP3133/LD/V004/IC26-8

RWE Generation

Aberthaw Power Station
The Leys
Aberthaw
Barry
South Glamorgan
CF62 4ZW

T +44(0)1446/75 02 71
F +44(0)1446/75 08 44
I www.rwenpower.com

Registered office:
RWE Generation UK plc
Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire SN5 6PB

Registered in England
and Wales no. 3892782

From: Lavisher, Amy [mailto:Amy.Lavisher@rwe.com]
Sent: 14 July 2015 08:39
To: Parr, Elizabeth
Cc: Leakey, Antony
Subject: RP3133LD- IC26-28 - Commissioning, operation & Performance report for the Carbon capture Pilot Plant - Confidential?

Hi Liz,

Both documents can be released publicly.

Kind Regards,
Amy Lavisher
Environmental Compliance Engineer
RWE Generation UK plc
Aberthaw Power Station, The Leys, Aberthaw, Barry, CF62 4ZW

Tel (Internal): 7-357-2270
Tel (External): +44 (0)1446 752270
Mobile: +44 (0)7920 833031
Fax: +44 (0)1446 750844 Mail to: amy.lavisher@rwe.com

From: Parr, Elizabeth [mailto:Elizabeth.Parr@cyfoethnaturiolcymru.gov.uk]
Sent: 13 July 2015 11:43
To: Lavisher, Amy
Cc: Leakey, Antony
Subject: RP3133LD - IC26-28 - Commissioning, operation & Performance report for the Carbon capture Pilot Plant - Confidential?
Importance: High

Hi Amy,

Further to my email below, the above report is also marked Confidential.

Please confirm that this document can be released publically.

Regards

Liz
From: Parr, Elizabeth
Sent: 13 July 2015 11:28
To: 'amy.lavisher@rwe.com'
Cc: Leakey, Antony
Subject: RP3133LD-IC23 - statistical analysis of Mercury - Confidential?
Importance: High

Good morning Amy,

The above report is marked as confidential, yet as a permit condition response it should be available for inspection on our Public Register.

Please confirm that this document can be released publically.

Thanks

Liz

Liz Parr

Cynorthwydd /Taff and Ely Industry & Waste Regulation Assistant

Cyfoeth Naturiol Cymru / Natural Resources Wales
Ffôn/Tel: 03000 653111
E-bost/E-mail:
Elizabeth.Parr@cyfoethnaturiolcymru.gov.uk Elizabeth.Parr@naturalresourceswales.gov.uk
Gwefan / Website: www.cyfoethnaturiolcymru.gov.uk / www.naturalresourceswales.gov.uk
Ein diben yw sicrhau bod adnoddau naturiol Cymru yn cael eu cynnal, eu gwella a'u defnyddio yn gynaliadwy, yn awr ac yn y dyfodol.
Our purpose is to ensure that the natural resources of Wales are sustainably maintained, enhanced and used, now and in the future.

- 6 JAN 2015

Commissioning, Operation & Performance Report for the Carbon Capture Pilot Plant – Improvement Condition 26-8

Aberthaw Power Station EP RP3133LD/V004

Reference Number: RP3133LD/V004/IC26-8

November 2014

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- see email dated 14/7/2015

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**RWE Generation UK plc Aberthaw Power Station
EP RP3133LD/V004**

**Commissioning, Operation & Performance Report for the Carbon Capture Pilot
Plant – Improvement Condition 26-8**

Prepared for Natural Resources Wales

This report has been produced to fulfil the requirements of Improvement Conditions 26-8 as part of Environmental Permit RP3133LD/V004.

The report summarises the commissioning and operational activities of the carbon capture pilot plant during the demonstration period. It includes a review of commissioning against the commissioning plan specified in pre-operational measure PM6 and a review of the environmental performance against the emissions monitoring protocol specified in pre-operational measure PM7. The report evaluates the emissions of residual amines and their reaction products, including nitrosamines and summarises learning points for future applications of carbon capture technology on combustion plant for power generation.

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1. Introduction

The purpose of the Aberthaw Carbon Capture Pilot Plant (CCP) Demonstration Project of RWE Generation UK (previously RWE npower plc) was to demonstrate the capture (absorption) and release (desorption) of carbon dioxide and sulphur dioxide from power station flue gas as a prospective part of a viable carbon capture and storage process, and to carry out a research and development programme to understand and evaluate this technology.

For this purpose, a CO₂ and SO₂ capture plant with the capacity to remove 50 tonnes/day of CO₂ from the station flue gas and including integrated SO₂ removal was designed and supplied for RWE Generation UK (hereafter called RWE) by Cansolv Technologies Inc, Montreal, a subsidiary of Shell Global (hereafter called CTI). The original intention of the project was to demonstrate the CCP process for 8,400 operating hours over two years; however, due to a number of unforeseen technical difficulties the plant's pre-commissioning and commissioning period was greatly extended. As a consequence the CCP had a very limited period of operation of 56 hours prior to its shutdown in April 2014.

The plant employed an amine scrubbing process which was operated to remove, in two separate cycles, both SO₂ and CO₂ from the station flue gas with a removal efficiency of up to 100% SO₂ and 90% CO₂. The capture process is based on post-combustion scrubbing techniques and uses a proprietary amine mixture owned by CTI.

The key technical features of the CCP plant included:

- Supply of flue gas from Unit 7 at Aberthaw.
- Booster fan to overcome pressure drop in CO₂ capture plant.
- Pre-scrubber water wash to cool flue gas and remove dust.
- SO₂ absorber to contact proprietary solvent 1 (SO₂ solvent) with flue gas to remove SO₂.
- CO₂ absorber to contact proprietary solvent 2 (CO₂ solvent) with flue gas to remove CO₂.
- Water wash to reduce loss of solvent from the process to <1ppm
- SO₂ regenerator to regenerate SO₂ solvent and release SO₂ as a gas.
- Amine Purification Unit to remove Heat Stable Salts
- CO₂ regenerator to regenerate CO₂ solvent and release CO₂ as a gas.
- Mechanical Vapour Recompression to reduce energy requirements.
- Package boiler and oil storage tank to raise steam for solvent regeneration.
- Sodium hydroxide storage and dosing for Amine Purification Unit regeneration.
- Return of treated gas, CO₂ and SO₂ streams to the power station stack.

A more complete process description is available in the updated Supporting Document (RP3133LD_Supp_Doc) submitted under pre-operational measure PM4.

For the purposes of this document and the avoidance of doubt, the term "Carbon Capture Plant" or "CCP" shall be taken to mean the whole plant, comprising of the SO₂ and CO₂ capture and release process plant supplied by CTI, as well as all ancillary plant and systems installed by RWE to support the CTI modules, such as the package boiler and other systems.

2. Commissioning

The commissioning process was carried out to ensure the mechanical, electrical and instrumental integrity of the plant and was split into several phases, as listed below:

- pre-commissioning
- cold commissioning – dry
- cold commissioning – wet (water)
- hot commissioning – water and steam
- process commissioning – solvents, caustic soda, flue gas, etc.

Following completion of the construction process, pre-commissioning and some dry cold commissioning activities commenced in September 2011 and were led by the principle contractor with assistance from RWE Generation UK. Once these activities were completed in each plant area a mechanical completion certificate was issued and responsibility signed over to RWE Generation UK for inclusion into their safety rules system, following the issue of a safety rules clearance certificate (SRCC). Safety rules clearance certificates were issued for most plant areas by end of December 2011, however some of the auxiliary systems were not signed over to RWE Generation UK until February 2012. For this reason different areas of plant could be in different commissioning phases at the same time.

During each phase of the pre-commissioning and commissioning process consideration was given to potential environmental risks and actions to be taken in the event of unexpected emissions. The following sections, 2.1-2.6, summarise the specific considerations, any unexpected emissions and actions taken to minimise any environmental impact.

2.1. Phase 1 – Pre-commissioning

This phase confirmed the mechanical and electrical completion of the plant and involved service tests, leak, pressure and QA checks. No process fluids were used during this phase, and consequently no additional environmental emissions were encountered in this phase.

A number of design and build issues were identified during the pre-commissioning phase, which required time-intensive remedial work. Issues with the plant emergency shut down (ESD) system, sea water ingress into instrumentation cabinets, the quality of fitted flange bolts, and weld quality issues in some of the steel work were identified and managed or resolved.

During the pre-commissioning phase a risk assessment was carried out of the potential occupational health impact of exposure of staff members to nitrosamines expected to be present as a degradation product in the amine mixture (Assessment of occupational risk of exposure to nitrosamines produced during laboratory and field based use of Cansolv solvents during operation of a carbon capture demonstration plant, Searl and Stelling, 2011).

The assessment was undertaken by the Institute of Occupational Medicine (IOM), Edinburgh and was conservatively based on the toxicity of NDMA (Nitroso-dimethylamine), which is the only Nitrosamine with a defined Workplace Exposure Limit (WEL), and which is widely held to be one of the most toxic nitrosamines (due to its high reactivity and mobility). In contrast, the nitrosamines expected to occur in the SO₂ and CO₂ solvents were assessed by an independent specialist consultancy to have a much lower health risk. In order to minimise the possibility of exposure to the nitrosamines, a retrofit of fully enclosed sampling systems to all liquid sample lines carrying amine solutions was carried out. This retrofit was also seen to minimise the risk of a release of process fluid during sampling activities.

2.2. Phase 2 – Cold Commissioning - Dry

This phase was concerned with commissioning of the online process monitoring equipment as described in Table 2.1 below.

Table 2.1: List of instrumentation with process monitoring functionality.

Device	Function
Online gas analysis package	Online gas analysis of all gas streams for CO ₂ , O ₂ , SO ₂
pH meters	Process and effluent control
Pressure indicators	Control of system pressures, including alarm functions
Temperature indicators	Control of system temperatures, including alarm functions
Flow meters	Control of system flows, including alarm functions

A number of issues with process monitoring equipment were identified and rectified during this stage. Many of these issues were thought to have occurred during transportation of the modules to site following overseas construction.

During this phase basic functionality testing of the online gas analysis system was initiated. Regular tripping and overheating problems were encountered that resulted in equipment failures and significant delays to this phase of the commissioning. The majority of the problems encountered were as a result of an incorrectly specified air conditioning unit and the location of internal thermal breakers inside an electrical cabinet within the gas analysis package. Repositioning of the thermal breakers and the fitting of door fans and vents in place of the air conditioning system solved the majority of the issues. Due to the unavailability of flue gas at this stage of commissioning full functional checking of the control system associated with the gas analysis package was not possible.

No additional environmental emissions occurred as a result of these delays.

This phase also included commissioning of the booster fan and flue gas ductwork using air, without any process fluids being introduced into the system. This part of the dry commissioning activity could only proceed after the handover of the plant to RWE Generation UK.

There was a minor foreseeable possibility of leaks from fan seals etc. during this phase and therefore, visual inspections for grease, oil and other fluid leaks were an added environmental protection measure started during this phase. Regular checks of the booster fan seals and bearings were conducted and a daily check of the lower plant area equipment was undertaken. No leaks of grease, oils or other fluids were observed during this phase of commissioning.

2.3. Phase 3 – Cold Commissioning – Wet (water only)

Wet commissioning was started in some areas of plant in December 2011. During this phase, cold demineralised water was introduced into the system for the purpose of flushing the circuits and proving integrity of pipework, pumps and other circulation equipment. This phase did not involve the addition of process steam or other chemicals to the plant.

Water samples were taken from each of the CCP plant circuits during the cold commissioning process for onsite analysis to determine any contamination from construction and for environmental monitoring. Analysis included a visual inspection for foaming, oil and grease, and analysis of pH and conductivity in the process water, with no significant contamination found (see Table 2).

Table 2.2: Sampling results from flush water during cold commissioning

9 th Jan 2012	Conductivity	pH	Suspended Solids	Visible Oil/Grease
Demin Blank	3.0 μ S/cm	n/a	0	0
SO₂ Circuit	31.5 μ S/cm	6.6	0	0
CO₂ Circuit	6.5 μ S/cm	7.0	0	0

Also included in this phase was hydro testing and tracer leakage testing of the Cansolv chimney tray located between the prescrubber and SO₂ absorber column. This chimney tray should allow flue gas to pass from the prescrubber to the absorber but should limit the passing of amine from the absorber to prescrubber, since the prescrubber was designed to discharge its effluent to the environment via the station's cooling water system.

In order to determine the maximum acceptable loss rate from the SO₂ circuit into the prescrubber, a calculation was made of the liquid loss that would represent a discharge into the environment (at station outfall) of 1% of the reference amine's PNEC (Proposed No-Effect Concentration) at minimum cooling water flow.

Initial hydro testing of the prescrubber-absorber chimney tray indicated that it was passing liquid at an approximate rate of 2 litres/hour (the water wash chimney tray was also later found to pass liquid at a similar quantity, see section 4). This rate of loss of liquid from the absorber was unacceptable and the tray manufacturers were asked to redesign the upper 'hat' component of the tray. Hydro testing with the redesigned chimney tray hats indicated that the loss of liquid to the prescrubber was still unacceptable, and the chimney trays were further modified to RWE Generation UK's specifications. The modified hats were then fitted and retested, both with and without air flow. No visual signs of liquid leakage could be seen, although some condensation on the bottom of the chimney tray was observed, which was attributed to the humidity of the ambient air condensing on the cold metal.

In order to confirm the loss rate from the system, ammonium sulphate was employed as a tracer to analyse the performance of the trays under operational conditions. Analysis of all samples for ammonium was undertaken using the Nessler test. The average concentration of tracer in the SO₂ circuit gave a leakage rate of 0.9 +/- 0.6 ml/hour. The top end of this leakage rate represents less than 0.01% of the PNEC entering the environment, which is significantly lower than the maximum permissible discharge limit (1% PNEC).

After completion of the cold commissioning phase, the flush water was discharged via the onsite oil interceptor system in accordance with the station's environmental permit. The volume of water used for cold commissioning of the CCP plant comprised approximately 22 m³.

The cold commissioning phase also included a demineralised water hydro test on the 55 m³ fuel oil tank to check the integrity of the tank prior to accepting the first delivery. The fuel tank does not sit within an external bund, but instead relies on a double skin to provide environmental protection should there be loss of integrity of the inner fuel holding tank. The integrity of the inner fuel containing component of the tank was found to be good, however small leaks were present in the walls of the outer skin. The tank was removed from site for repair and hydro testing at the supplier's premises. On return to site the outer skin of the tank was again hydro tested and found to be sound. The volume of the water used for onsite hydro testing of the tank was approximately 75m³ and this was discharged via the onsite oil interceptor system.

During February 2012 a failure was experienced in an existing Station underground pipe used as part of the tie in to the CCP sea water cooling system. This delayed testing of the sea water pump, which was eventually completed late March 2012.

2.4. Phase 4 – Hot Commissioning – Water and Steam

Hot commissioning commenced in May 2012. During this phase, the plant was running filled with water and air, and steam was introduced to the process via the auxiliary package boiler. This allowed testing of the plant response to temperature and pressure gradients, as well as observation of real instrument readings from the process without the need to introduce amines as process fluid. The emissions expected during this phase included process waters, as in Phase 3, and gaseous emissions from the package boiler.

Package Boiler commissioning and operation

The purpose of the Package Boiler is the introduction of stripping steam into the CCP Plant via tubed heat exchangers. The boiler operates in a closed loop with no direct steam injection into the process. Prior to commencement of hot commissioning, the site accepted a single delivery of 36,000 litres of distillate fuel oil in order to part fill the oil tank. The delivery was accepted in accordance with an approved procedure and there were no spillages or other problems during the delivery.

The Package Boiler was fired and commissioned by the Vendor. Combustion emission data recorded by the vendor during commissioning, for both boiler low and high fire settings, is presented in Table 2.3 below.

Table 2.3: Combustion data obtained from package boiler during commissioning

	Date	O ₂ (%)	CO (ppm)	NO (ppm)	NO ₂ (ppm)	NO _x (ppm)	CO ₂ (%)	Effic. (%)
Low Fire	20.06.12	6.3	0	54	0	54	10.8	89.8
High Fire	21.06.12	4.1	2	72	2	74	12.4	89.4

Boiler water dosing chemicals were also introduced during this phase. A boiler dosing regime based on trisodium phosphate and morpholine was adopted to provide alkalisation.

Carbohydrazide was dosed into the boiler as an oxygen scavenger to obtain oxygen levels <20ppb. The chemicals were dosed from 25L carboys which were prepared from the pure ingredients in the station lab and housed in a bund within the boiler house. No chemical spillages or leaks were encountered throughout the lifetime of the plant. Package boiler blowdown was discharged to the station drains; regular sample analysis showed that the chemical content was negligible at all times from an environmental perspective (<15ppm Phosphate, <5ppm Morpholine).

Steam and condensate system commissioning

Following successful commissioning of the Package Boiler, steam and condensate flows were established around the CCP. Checks carried out before and during the hot commissioning programme showed an absence of leaks .

Upon completion of hot commissioning the SO₂ and CO₂ circuits were drained via the Station's oil interceptors (approximately 22 m³ of water).

The mechanical vapour recompressor (MVR) unit was a device installed on the plant with the intention of investigating potential energy savings that may be possible during stripping of CO₂ by replacing some of the latent heat at the reboilers with compression energy. The original plan was for this to be commissioned by the vendor during this phase, however this commissioning never occurred at this stage. Ultimately, the MVR unit was never put into service because of the delays to commissioning and the lack of availability of the vendor's commissioning engineers.

Laboratory analysis methods were finalised and validated during this phase. Details of the analysis methods, together with the Limits of Detection determined, can be found in the PM7 document (v4) submitted to NRW on 19/08/2013.

2.5. Phase 5 – Hot Commissioning – Process Fluids

Prior to commencement of process commissioning, the site accepted a delivery of 127 x 205 litre drums of CO₂ amine concentrate, 8 x 205 litre drums of SO₂ amine concentrate, 20,000 litres of 20wt% sodium hydroxide solution for process use, and 3x25L of 96% Sulphuric Acid for conditioning of the SO₂ amine. The deliveries were accepted in accordance with an approved procedure and there were no spillages or other problems during the deliveries.

Process commissioning was carried out separately for the APU (Amine Purification Unit) and the SO₂ and CO₂ scrubbing circuits. After filling of the APU, the SO₂ process was commissioned and shown to be running to an acceptable standard before commissioning the CO₂ process. At this stage the flue gas duct was de-isolated and flue gas introduced into the CCP plant. The composition of all gas streams was monitored by the online gas analysis system, and the combined scrubbed flue gas returned to the station stack.

APU filling

The APU was filled with anion resin in accordance with an approved procedure. The resin bed underwent double regeneration with 4%wt Sodium Hydroxide (diluted from 20% stock) before being put in service. The alkaline regeneration effluents for the APU were collected in a holding tank as per the approved procedure. Once the APU Effluent tank was filled (during the following Process Commissioning period), the contents were analysed and discharged to the Prescrubber for neutralisation by the incoming flue gas, followed by discharge to the station's cooling water circuit. Analysis data for the APU Effluent tank contents prior to discharge can be found in Section 3.2.

Filling of the SO₂ system with amine

This phase commenced by filling the SO₂ lean amine tank with the required amount of SO₂ amine from drums positioned within the bunded area adjacent to the CCP. The SO₂ amine was then salted by the addition of sulphuric acid and subsequently diluted to the correct operating concentration using demineralised water. An atmospheric GasTec tube test was undertaken during the salting process to confirm the absence of volatile amines (refer to Section 3). Personal gas detectors were worn throughout the activity and no release of SO₂ gas was detected. Drums were flushed back to the process with small quantities of demineralised water and stored on site in a chemical storage area prior to disposal via the Station's onsite waste contractor.

Filling of the CO₂ system with amine

The initial filling of the CO₂ process occurred by pumping the concentrated CO₂ amine into the CO₂ Lean Amine Tank from drums positioned within the bunded area adjacent to the CCP. Drums were flushed back to the process with small quantities of demineralised water and stored on site in a chemical storage area prior to disposal via the Station's onsite waste contractor. During this activity atmospheric Gas Tec tube testing confirmed the absence of volatile amine.

2.6. Process Commissioning (System Tests) and System Operation

Following commissioning of the SO₂ and CO₂ circuits, a series of controlled experiments were carried out to prove operability of the system.

SO₂

Once the amine had been adjusted to the required working amine concentration and baseline salt levels, regular sampling was undertaken from the installed sample points so as to monitor the amine concentration, the amine loading and the amine condition (breakdown products, heat stable salt levels etc.).

The SO₂ circuit was operated in line with CTI's commissioning programme to try to maintain correct water balance within the system whilst targeting the required SO₂ slip to the CO₂ absorber (30 mg/Nm³ or 11.5 ppm wet, as defined by CTI). SO₂ slip was measured by the online gas analysis system, and this measurement was also used for process protection of the CO₂ system by tripping the plant if high levels of SO₂ slip were detected. Gas monitoring was undertaken to confirm the absence of fugitive amine emissions.

During operation of the APU it was found that stratification and poor mixing of different density process liquids could occur within the SO₂ lean amine tank (fully salted amine, returned amine from the APU, and flush water). This led to inconsistent analysis results, and could reduce the performance of the SO₂ absorption process leading to a sudden increase in SO₂ slip to the CO₂ absorber. A spill back line was designed and implemented by RWE so as to improve mixing in the SO₂ lean amine tank and prevent stratification of different density liquids. Multiple cycles of APU operation with demineralised water rinse was found to greatly affect the SO₂ system water balance to an extent where it couldn't be removed by the adjustment of operational parameters. The excess water had to be removed from the system by operator controlled reflux purge off to the effluent tanks, and during this time flue gas couldn't be contacted. To significantly reduce excess water entering the SO₂ system, the APU cycle was modified to use SO₂ reflux from the process in place of a large proportion of the rinse water. This required additional safety measures to be put in place. It was found that low levels of SO₂ gas could be released from effluent tanks in to the bund. As the design of the effluent tanks could not be altered the SO₂ release was controlled by caustic slugging of the tanks to ensure any effluent present was slightly alkaline in pH before any reflux was transferred.

CO₂

The CO₂ circuit was commissioned in line with CTI's commissioning programme and adjustments made to target the correct operational conditions required to maintain water balance and 90% CO₂ removal rate. Regular sampling was undertaken from the installed sample points so as to monitor the amine concentration, the amine loading and the amine condition (breakdown products, heat stable salt levels etc.).

Online gas analysis of all gas streams were captured to document the composition of the gases, samples from the rich and lean amine as well as from the absorber water wash sections were taken and analysed, and the plant was routinely checked for liquid and vapour leaks. CO₂ gas testing (using gas monitors) was undertaken to confirm the absence of fugitive emissions.

The water wash system chimney tray was found to lose water to the CO₂ absorber process when operated. Here the loss of liquid did not present an environmental discharge risk so the operation of this system was procedurally controlled. Level was adjusted at start-up to ensure that sufficient volume was contained within the system, and the wash water system was only operated during flue gas contact.

The original plan for moving out of the commissioning phase into the R&D operational phase was when the plant performance complied with the agreed performance criteria, and correct operation of both amine circuits had been demonstrated for a period of 30 days without any defect that would affect the CO₂ capture capability of the plant. Due to delays in commissioning, the 30 day demonstration period was reduced and the plant was designated to be fully commissioned in March 2014, prior to the commencement of the environmental survey.

2.7. Summary of Commissioning Issues

The following section summarises the main commissioning issues which had the potential to affect the environmental performance of the CCP. Where issues were identified corrective action was implemented and as a result there were no uncontrolled discharges from the plant into the environment.

Main plant amine leaks

A number of amine leaks were found and addressed throughout the commissioning and operation of the plant. The majority of the leaks were minor weeps from valves or flanges, directly into the main plant bund, which were discharged via the APU effluent tanks in accordance with the approved procedure (see Section 3.2). During process commissioning, very small amounts of amine were found to be slowly leaking from the CO₂ reboiler, which is located over the main plant bund. Measures were put in place to contain the leak which was mostly confined to the lagging. Both reboilers were removed from site for inspection, gasket replacement and testing. On their return to site, onsite testing, relagging and further modifications to the system delayed the return to service of the reboilers until October 2013. Another issue was also identified with the SO₂ circuit resulting in increased amine in the APU (described in Section 2.6). Measures were put in place to improve the SO₂ circuit and APU operation and the contaminated APU water was dealt with in accordance with the approved procedure (see Section 3.2). Just prior to the scheduled second environmental testing campaign, the CO₂ reboiler was found to be leaking amine again so operation of the plant was discontinued.

Amine contaminants

During the early stages of process commissioning, SO₂ and CO₂ reflux samples, as well as one sample of liquid recovered from a drain vent in the flue gas return to the power station, were found to have a pronounced odour and slightly elevated conductivity. Qualitative analysis of these unusual samples was undertaken by HSL and Cansolv and showed the presence of volatile organic contaminants. On further investigation these were found to originate from the manufacturing process of the solvents, representing minor impurities in this particular batch. In addition, some compounds (e.g. 1,4-Dioxane) were also found to be present in very small concentrations in the incoming flue gas (see Table 3.6), and may have accumulated in the solvent/reflux from this source. Due to their high volatility compared with the solvents themselves, they were boiled out quickly during initial operation and subsequently concentrated in the reflux drums.

The total amount of contaminants in the solvent was conservatively estimated to have been ten times that found in the amine samples (given that a proportion had already evaporated). An assessment was then carried out using the two most environmentally harmful species and calculating the stack concentrations based on the assumption that the full inventory would be evaporated within a 8-hour period. The results were then compared to the Environmental Assessment Level (EAL) values published in the H1 guidance of the Environment Agency and found to be two orders of magnitude below without allowing for dispersion. It was therefore assessed that the contamination had no environmental impact.

Bund drainage

Some issues were experienced with inconsistent slopes in bunds which led to problems during discharge. To account for the possibility of incomplete bund mixing prior to any discharge, the water was tested in at least 4 different locations so as to ensure that the pH was in the 6-8 range across the bund.

Table 2.4 below summarises the commissioning issues which had the potential to affect the environmental performance of the CCP and details the changes implemented to resolve those issues.

Table 2.4: Engineering changes affecting environmental performance

	Description of Issues	Action/changes/outcome adopted
1	Chimney tray located between the prescrubber and SO ₂ absorber was passing significant and unacceptable quantities of liquid.	Tray design modified to achieve sufficiently low emissions. See section 2.3
2	Process fluid sampling points on plant originally consisted of simple-valved offtakes which could have exposed operators to amine derived nitrosamines during sampling.	Fully enclosed sampling system, see Section 2.1.
3	High temperatures (>40°C) in the CEMS cabinets causing analyser faults, plc failure and thermal tripping.	Problems rectified, see section 2.2
4	Insufficient volume in SO ₂ lean amine tank to allow multiple APU cycles with demineralised water flush without having to remove water from the system. APU operation greatly affects SO ₂ system water balance.	<p>Original concept to use SO₂ reflux changed following HAZOP due to concerns over SO₂ gas release from effluent tanks. Reflux line to APU still present but isolated and locked off.</p> <p>Idea revisited and appropriate safety measures put in place (hardwired slam shut valves, gas detector in effluent tank bund etc.) once water balance problem became known.</p> <p>It was found that low levels of SO₂ gas could be released from effluent tanks to bund (detector alarm activated). SO₂ release controlled by caustic slugging of tanks as design could not be altered at late stage of project.</p>

	Description of Issues	Action/changes/outcome adopted
5	<p>Design of the chimney tray between the CO₂ absorber and water wash section.</p> <p>Water is lost from water wash chimney tray to CO₂ absorber leading to dilution of amine solution.</p> <p>There is no automatic water make-up. Design incorporated water makeup via condensation, but on start-up water wash liquid levels drop due to there being low amine and duct temperatures (no condensation).</p>	<p>As long as operating level maintained some loss of water from water wash to CO₂ absorber can be tolerated and will not result in increased amine carry over in the exiting flue gas. Therefore chimney tray not redesigned (as prescubber-SO₂ absorber tray was).</p> <p>Water wash stopped when flue gas stopped and correct operating level maintained on start-up with operator intervention.</p>
6	No suitable 4" iso-kinetic sampling ports fitted.	See section 3.3.

3. Environmental Analysis

This section provides details of plant performance and the results of environmental monitoring throughout the lifetime of the CCP. Section 3.1 summarises the environmental performance over the lifetime of the plant, while sections 3.2 and 3.3 contain information on specific plant emission monitoring results.

Emissions to the environment from the CCP Plant arose through the following routes:

- Liquid effluent from regeneration of the APU Resin, collected in the APU Effluent Tanks and discharged via the Prescubber to the Station's Cooling Water System.
- Combustion gas emissions arising from operation of the Package Boiler.
- Emissions from the CCP process present as impurities in the treated and recombined flue gas as returned to the Station stack.
- Fugitive emissions from the CCP process.

Point b is addressed in Section 3.1; a and d are reviewed in Section 3.2, while an estimation of emissions according to point c is provided through the results of the Environmental Survey in Section 3.3.

3.1. Summary of Environmental Performance

Table 3.1 below summarises totalised figures of plant performance over the course of the CCP project, including commissioning.

Table 3.1: Key Environmental Performance Data

Parameter	Time Period	Total Amount	Unit
Flue Gas received	10.01.13 - 24.04.14	1458446	Nm ³
CO ₂ captured	10.01.13 - 24.04.14	150943	Nm ³
SO ₂ captured	10.01.13 - 24.04.14	585	Nm ³
Fuel oil used	23.05.12 – 28.05.14	99.09	tonnes
APU Effluent discharged	13.11.12 – 24.06.14	149.7	m ³

It should be noted that the fuel consumption relates to the total amount used for the CCP and not to the consumption for flue gas capture only. Due to the limited duration of the operational period it was not possible to complete an energy optimisation of the CCP process, and consequently CO₂ capture energy requirements have not been published.

Combustion gas emissions from Package Boiler

Throughout the project, 99.09 tonnes of gas oil was used to fuel the package boiler. The calculated estimated emissions from combustion of this fuel are shown in Table 3.2.

Table 3.2: Package Boiler Mass Emissions¹

Emission	Amounts (tonnes)
Particle Matter (PM) ²	0.001
Carbon dioxide	312
Oxides of nitrogen (as NO ₂) ³	0.32
Oxides of Sulphur (as SO ₂) ⁴	0.003

¹The calculation methodology is based on methods given in JEP Pollution Inventory 2013: Electricity Supply Industry Methodology, Weatherstone, S, Jan 2014.

²Although the particulate emissions associated with gas oil will be negligible, an emission factor of 0.72mg/l (US EPA AP-42) has been used to estimate the particulate emissions from the package boiler. The manufacturer's specification for the ultra-low sulphur gas oil gave the typical ash content as 0.001%(m/m).

³The emission factor for NO_x as NO₂ (0.003205 t/t) is derived from an exit concentration of 260 mg/Nm³ NO_x as NO₂ at 3%O₂ provided by the package boiler manufacturer; a typical net calorific value of 42.5 MJ kg⁻¹ for the gas oil and the JEP default volume factor for oil of 0.29 Nm³ MJ⁻¹ at 3% O₂.

⁴The manufacturer's specification for the ultra-low sulphur gas oil gave the typical sulphur content as 8.8 mg/kg.

Waste

All non-amine waste generated during the commissioning or operation of the plant was disposed of via the standard Station segregated waste streams already in place and the site Station approved waste contractor, Celtic Recycling Ltd and are not reported here. Disposal of all amine/amine contaminated waste generated from the plant was arranged via Celtic Recycling Ltd. Amine/amine contaminated waste streams included solid waste (amine contaminated drums, cloths, gloves, resin beads, plant filters and respirator cartridges etc.) and liquid waste (plant samples, contaminated effluent, contaminated bund water, contaminated reflux, amine/flush water at end of project) .

Each of the various waste streams generated from the plant are presented in Table 3.3 below. The bulk amine total includes flush water and 47,150 litres of remaining unused amine disposed of at the end of the project.

Table 3.3: Waste

	Amount (tonnes)
<u>Bulk amine/amine contaminated flush water</u>	<u>187.9</u>
<u>Bulk NaOH/NaOH flush water</u>	<u>20.8</u>
<u>Small amine lab/sampling waste</u>	<u>0.3</u>
<u>Amine contaminated solid waste</u>	<u>0.3</u>

3.2. Results from Routine Environmental Testing

APU Effluent tank analysis

The main source of emissions from the CCP was through the APU regeneration process. The APU, an anion exchange bed, was operated to remove Heat Stable Salts (HSS) from the process amines in order to maintain the functionality of the solvent. The main salt removed was Sulphate, which is formed from oxidation of sulphite in the SO₂ circuit. In comparison, the amount of HSS accumulated in the CO₂ circuit proved to be much smaller. The resin was regenerated with 4% NaOH (see also Section 2.5) to allow for the removal of accumulated salts from the bed. Although the resin column was flushed with demineralised water to displace most of the amine present prior to regen, a certain amount of amine was discharged with the regenerant, and was therefore collected in the APU effluent tanks.

Some other streams were also added to the APU effluent tanks on an occasional basis throughout the commissioning process, as this allowed for good control of the quality of any liquid discharge to the environment. Such streams included: *SO₂ and CO₂ Reflux* from the Reflux accumulators – these were distillates composed mostly of water with small amounts of amine and dissolved product gases, and *Bund Water* from the CPP Plant Bund in instances when small leaks from the plant had been experienced and when a contamination with amine could not be excluded (see Section 2.7 for details).

The contents of the APU effluent tank were in all cases mixed using a fixed installed motorised paddle stirrer, sampled, and analysed for Total Kjeldahl Nitrogen (TKN) as a proxy for amine concentration prior to discharge. PM7 provides a calculation of the allowable discharge from the APU effluent tanks to the Prescrubber in order to not exceed 4% PNEC upon discharge to the environment. (see Table 3.4 below).

Table 3.4: Discharge Limits for APU Effluent

TKN Level		TKN mg/L	Actions	Discharge Requirements
"Normal"		0-100	none	min. 1x CW in service
"Elevated"		100 – 200	Investigate	min. 1x CW in service
"Quarantine"		200 - 300	Quarantine Tank Investigate	Investigation Resolved; min. 1x CW in Service
"Tanker"		> 300	Plant Shut Down Full Investigation	Removal by Tanker Only

APU effluent analysis throughout the project is shown in Table 3.5. The analysis data gave varied results, which were generally slightly higher than expected. This was due to the need to minimise the amount of APU flush water returned to the unit in order to maintain the water balance in the system, a process which was optimised in February/March 2014 as detailed in Section 2.6. During the optimisation, a number of measurements in the region of 200-300ppm TKN occurred as well as one sample which gave a result >300ppm. These instances were investigated and finally resolved using an improved APU process cycle which satisfied the demands both of a reasonable discharge and the water balance requirements in the system.

APU tanks containing 200-300ppm TKN were discharged after investigation and only when several of the station's Cooling Water pumps were in service (which effectively reduced the concentration emitted to the environment by a factor of 2 or 3). The APU tank giving a result >300ppm TKN was disposed of offsite as hazardous waste in accordance with the agreed procedure.

Table 3.5: APU Effluent Tank Analysis

Date	TANK #	pH	TKN (mg/L)	TOC (mg/L)	Comment
13/11/2012	A	5.6	35		
05/02/2013	A	5.2	18		no discharge instructed
15/02/2013	A	6.4	218		APU cycle malfunction; discharged after investigation
19/04/2013	B	5.9	50		
13/06/2013	A		43		
17/06/2013	B		244		Reboiler flush; discharged after investigation
20/09/2013	A	5.6	48		
06/11/2013	A	6.2	156		Discharge instructed
25/02/2014	B	6.3	290		High value due to amine in SO ₂ reflux. 2CW pumps in service; discharged next day
26/02/2014	A	8.9	>300		High value due to amine in SO ₂ reflux. Tanker called to remove amine. No discharge
20/03/2014	B		244		APU flush readjustments. 2 CW pumps in service, discharged via prescrubber
25/03/2014	A	8.4	274		APU flush readjustments. 2 CW pumps in service, OK to discharge
01/04/2014	B	6.7	95		Sampled. OK to discharge
02/04/2014	A	12.9	144		Sampled. Discharge unclear.
10/04/2014	B	8.6	148		Discharged.
17/04/2014	A	6.5	102		Discharged.
08/05/2014	B			50	Decommissioning Effluent. Discharged.
09/06/2014	A			87	Discharged.
12/06/2014	A			<50	Discharged
13/06/2014	B			<50	Discharged
24/06/2014	A			<50	Discharged

Fugitive emissions from the plant

Measurements of fugitive emissions from the plant were undertaken in regular intervals throughout the course of the project. Such measurements started during tank filling (in October 2012) and first gas contact (Jan 2013) to check for fugitive leaks of amine and SO₂/CO₂ product gases. For amine checks, an amine specific GasTec tube was used as a qualitative measure, while personal gas monitors were used for fugitive emission checks for SO₂ and CO₂. While no amine vapours were detected during filling and throughout the project thereafter, a small SO₂ leak was spotted during first gas contact. This resulted in abortion of operation, clean-out of plant and fixing of the leak. During the following start-ups, no further leaks were detected.

Regular checks using GasTec tubes and personal monitors were carried out quarterly, although tests were suspended while the plant was shut down. No further fugitive leaks were detected during these campaigns.

Fixed SO₂ monitors connected to audiovisual alarms are fitted to the plant in 3 locations to spot any SO₂ leaks in the areas of highest potential exposure risk (APU effluent tank bunds, SO₂ reboiler area, outside the control room). Throughout early operation, some instances of spurious alarms were detected, one of which was afterwards associated with emissions from a lorry stopping outside the perimeter fence near the alarm. However, during the course of the project, RWE Generation UK became aware of a possibility of SO₂ leaks from the atmospheric vent of the APU Effluent tanks. These may occur in certain operational conditions associated with water balance issues in the SO₂ circuit, and required careful plant management to avoid SO₂ release. These issues had not been anticipated at the design stage of the plant, but needed to be addressed during the final stage of commissioning in March/April 2014. During this period, SO₂ was detected inside the APU bund in three instances, resulting in an automatic CCP Plant shutdown. Following successful implementation of an amended water balance procedure, the releases did not reoccur, see section 2.6 for further details.

Further GasTec testing for amine vapours was carried out during the decommissioning stage, while the amine from the plant was transferred into waste tankers for disposal. No fugitive emissions were detected.

A measurement of fugitive noise emissions carried out during hot commissioning, with the boiler operating and the loops in circulation, demonstrated the noise levels to be acceptable (<80db). The major contributor to noise pollution was expected to be the MVR which was never commissioned.

3.3. Environmental Survey

Following completion of the plant commissioning, an environmental survey was carried out in April 2014, which included monitoring of the treated gas streams for amine carryover and volatile nitrosamines. The survey involved a coordinated sampling exercise of all process and environmental sample streams (gaseous and liquid), and analysis for an extensive range of chemical and environmental parameters. The analysis was carried out by RWE, Cansolv Technologies, Intertek Ltd and HSL and included GC analysis of samples from the flue gas and CO₂ product streams, impinger sampling of flue gases with analysis for amines and nitrosamines, as well as anion chromatography, LC-MS and ICP analysis of liquid samples.

A second environmental survey was planned for the end of May 2014 but had to be abandoned following detection of a leak in the CO₂ circuit reboiler which led to early termination of the test series. Unfortunately this means that the results reported below represent only one data point, and an assessment of their accuracy, precision and significance is difficult to achieve. Given the difficulties associated in particular with the gas sampling (as described below), it is advised to treat the reported figures as purely qualitative to within an order of magnitude.

Gas analysis

Online gas analysis was undertaken using a Horiba PG250 analyser in order to compare results with the installed gas analyser package. This was complicated by the fact that online analysis could not be undertaken simultaneously, and that absorption conditions during the survey were not stable, as impinger sampling, which was carried out at the same time, required several plant shutdowns.

Overall, results were comparable, with the Horiba producing slightly smaller values for CO₂ and SO₂ content and slightly higher values for O₂ content than the installed package. This might be attributed to differences in sample line layout (e.g. heat tracing), flue gas composition (all values are averages over a timespan) and calibration. CO and NO_x concentration was only measured on the Horiba. The analysis shows that CO₂ capture exceeded 90%, while SO₂ capture was complete. It is unclear whether the observed changes in CO and NO_x concentrations and the discrepancies before and after the water wash are significant or due to experimental error.

In order to determine the amount of amine and nitrosamines carried over into the treated flue gas, impinger sampling was performed on the inlet flue gas, as well as the treated gas both before and after the water wash section. During the planning process it was discovered that the sampling flanges were not sized for isokinetic sampling, and that the internal pressure and moisture content of the absorber column presented a challenging environment for sampling. A shutdown of the plant was required to allow safe insertion of the probes into the gas stream, which compromised the comparability of the test points. Gas samples were bubbled through water filled impingers and the resulting solutions analysed using LC-MS; the resulting results are expressed as mg/m³ Kjeldahl Nitrogen for amines, and mg/m³ NNO for Nitrosamine for comparability. Impinger solutions showed a 100% capture rate for amines and a 50-80% capture rate for Nitrosamine.

Gas analysis for trace volatile organic compounds was carried out by sampling onto an absorbent medium and analysis by HSL. The sample points for these were located on the online gas analyser module, rather than directly on the process column. 3 samples were collected at each sample point, and the results averaged. Formaldehyde samples underwent solvent desorption, while other VOCs were thermally desorbed. All compounds were identified and quantified using GC-MS.

Table 3.6: Gas Sample Analysis Results

Sample Point	Flue Gas Inlet	Pre Water Wash	Post Water Wash
<i>Online Gas Analysis</i>			
O ₂ (%)	6.26	7.64	6.93
CO ₂ (%)	12.9	0.91	1.07
CO(ppm)	444	276	529
NO _x (ppm)	427	482	486
SO ₂ (ppm)	956	-1	-1
<i>Impinger Analysis</i>			
Amine (mg TKN/m3)		10	4

Sample Point	Flue Gas Inlet	Pre Water Wash	Post Water Wash
Nitrosamine (mg NNO/m3)		0.2	1.1
Degradation Products (mg/m3)		0	2
Trace Volatile Organics (as ppm airborne)			
Formaldehyde	0.01	0.023	0.02
Acetaldehyde	0.015	0.4	0.063
Acetonitrile		0.01	0.012
Benzene	0.005	0.003	0.002
Toluene	0.009	0.001	0.001
Dioxane	0.021		
Pyrazines		0.014	0.005
Benzaldehyde		0.008	0.004
Benzoic Acid		0.004	0.003

Liquid sample analysis

All liquid process streams were sampled during the Environmental Survey, and samples were analysed by RWE, CTI Technologies (LC-MS) and Intertek (ICP-MS). The purpose of amine sampling was to close the mass balances and achieve an image of the plant in equilibrium at a particular time. This goal was not completely achieved due to the requirement for shutdowns imposed by the impinger method, which did not allow for a single plant condition throughout the sampling exercise; however, the mass balance of the process fluids was correct to within 2% for all samples, and the mass balance analyses from RWE and CTI compared well.

Analysis results for samples of environmental significance is provided below in Table 3.7; this includes the APU and Prescrubber effluent (which represent discharges to the environment), and the Water Wash of the final treated flue gas, which is designed to reduce the amount of amine carried over with the final flue gas.

Analysis of the Water Wash sample shows that amine is effectively removed by the process, although not all the TKN measured is due to the process amine. The amine removal is attributed to the solubility of the amine vapour in water rather than mechanical carry-over, which is demonstrated by the low amount of heat stable salts in solution. The water-wash is periodically returned to the CO₂ amine circuit to maintain the water balance.

Analysis of the APU effluent shows the effective removal of salts, in particular from the SO₂ circuit coupled with a moderate uptake of amine from the APU rinse solution. The prescrubber was not receiving APU effluent at the time of the analysis, so that the trace metal analysis shows the level of leaching from flue gas ash to be low.

Table 3.7: Liquid Sample Analysis Results

Sample Point		Water Wash	APU Effluent	Prescrubber Blowdown
<i>Principal Analysis (RWE/CTI)</i>				
pH		8.6	12.9	2.5
Conductivity	mS/cm	0.39	35.4	2.2
Susp. Solids	mg/L		6	88
Total Kjeldahl Nitrogen	mg/L TKN	141	144	4
Amine Content	mg/L TKN	82	110	0
Nitrosamine Content	mg/L NNO	3.6	0.3	0
Degradation Products	mg/L	0	0	0
<i>Ion Chromatography (CTI)</i>				
Fluoride	mg/L	ND	ND	76
Chloride	mg/L	ND	ND	112
Sulfite	mg/L	ND	6400	ND
Sulfate	mg/L	5	3500	300
Nitrate	mg/L	<5	ND	<50
Organic Acids	mg/L	<5	<500	ND
<i>Metals by ICP-MS (Intertek)</i>				
Ag	mg/L		<0.3	<0.3
Al	mg/L		<2	7
As	mg/L		<2	<2
B	mg/L		1	5
Ba	mg/L		<0.1	0.2
Ca	mg/L		3	66
Cd	mg/L		<0.1	<0.1
Co	mg/L		<0.6	<0.6
Cr	mg/L		<0.3	<0.3
Cu	mg/L		<0.2	<0.2
Fe	mg/L		1	4
K	mg/L		<10	<10
Li	mg/L		<0.3	<0.3
Mg	mg/L		<0.1	16
Mn	mg/L		<0.1	<0.1
Mo	mg/L		<0.6	<0.6
Na	mg/L		7710	27
Ni	mg/L		<1	<1
Pb	mg/L		<3	<3
Sb	mg/L		<2	<2
Se	mg/L		<3	<3
Si	mg/L		3	15
Sn	mg/L		<0.7	<0.7

Sample Point		Water Wash	APU Effluent	Prescrubber Blowdown
Sr	mg/L		<0.1	0.5
Ti	mg/L		<0.1	0.3
V	mg/L		<0.3	<0.3
Zn	mg/L		0.5	0.6

4. Learning Points for Future Installations

The engineering and operational challenges encountered throughout the Aberthaw CCP Project gave rise to a large number of learning points which may be of use for scale-up and future installations. A number of items with potential environmental significance is listed below.

- It is recommended that all subsequent reboiler designs used on carbon capture plants are capable of frequent ramp cycles so as to accommodate different power station operating regimes. All reboilers should be fitted with appropriate high point vents and local flush and isolation points.
- Ensure sizing of pumps allows sufficient turn up or turn down so as to enable the use of alternative solvents, or to allow the investigation of alternative operating modes that may be less energy efficient but more capital efficient.
- Ensure the plant design does not include atmospheric venting in any areas of plant containing amine solvent, due to the potential for the localised release of nitrosamine species. All vent lines should be routed back to the process.
- Ensure lean amine tanks are sized to allow total volume of inventory to be stored with headroom to spare so as to allow total emptying of the remaining system during invasive remedial work.
- Ensure fall on plant bunds is to a single designated low point so as to ensure proper drainage and no hang up of liquid. It is recommended that the main plant bund area is constructed in sections, and that flow of liquid from individual sections to the designated discharge point be placed under operator control. This means that in the event of a localised amine leak only one section is affected, and limits the amount of flush water required for clean-up.
- Fully enclosed sampling systems. The use of fully enclosed sampling systems is recommended wherever it is likely that the process fluid or gases contained in the process fluids carry serious health or environmental risks. For carbon capture amines, this may be justified if an issue with Nitrosamines is expected.

- Vent lines to be routed back into the process. It may be necessary to route any atmospheric vent lines (other than overpressure safety valves) to return to a convenient point in the process, especially if issues either with harmful fugitive amine emissions or with toxic gases such as SO₂ are expected. Similarly, regularly used amine filled drain lines (e.g. in filtering equipment) should be routed back to a holding tank or to the process.
- Waste Tank Specifications. In pilot plants it may be necessary to use process reflux for maintaining water balance, in which case it may be beneficial to specify non-atmospheric waste tanks in order to be able to contain any potential gaseous emissions. In addition, dosing and mixing equipment should be provided in waste tanks to allow for adjusting the tank conditions to minimise potentially harmful effects.
- The risk of reboiler and heat exchanger leaks can be minimised by using welded or tubed rather than plate/frame gasket type equipment.
- Wherever cross-contamination of amine and water circuit systems can occur within the same column (Prescrubber, Water Wash etc.), close attention should be paid to the quality of the chimney tray design between the sections to minimise cross contamination. However, more complicated tray arrangement may lead to increased pressure drop across the column, which should be factored in. It is recommended that, where space permits, a pre-scrubber and absorber should not be combined in a single vessel.
- Sufficient heat tracing and insulation is paramount for maintaining stable process conditions. This may be less pertinent on larger plant, where the surface-to-volume ratio is smaller.
- In the solvent specification, attention should be paid even to small amounts of impurities which may not require listing on the MSDS. In particular where such compounds are sufficiently volatile to escape via the treated flue gas or product stream. However, it may be difficult to demand full analysis of the process fluids, since most systems are subject to commercial confidentiality, and manufacturers are cautious of releasing data into the public domain that may infringe on the IP.
- Especially for plants designed and manufactured outside the EU, controls are required to ensure that all items are CE marked as required.
- Sampling ports should be sized for isokinetic sampling (4" ports), be located in accessible locations and be shut off by a suitable valve arrangement. It should be a design feature to allow the insertion of temporary gas sampling equipment into the process without requiring a prior plant shutdown.
- The system should have sufficient volume and mixing characteristics to allow for simple maintenance of the water balance.

The small number of post-commissioning operating hours resulted in a very limited dataset being obtained from the plant. The data that were collected are considered insufficient to reliably predict the future performance of an up-scaled Carbon Capture Plant using this or a similar solvent. In addition, the environmental emission data collected during the Environmental Survey only represents one data point, which makes it impossible to assess the reliability of the estimated emissions. It is therefore not feasible to speculate on either the potential energy penalty or environmental impact such a full scale combustion plant would produce.

RWE Generation UK plc

RWE Generation UK plc
Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire
SN5 6PB

T +44 (0)1793 877777
F +44 (0)1793 892525
I <http://www.rwegeneration.com>

Registered Office:
RWE Generation UK plc
Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire
SN5 6PB
Registered in England
& Wales: No. 3892782

