Flexibly-operated capture using solvent storage

CCUS Innovation 2.0

Key Knowledge Deliverable 4.1 – Initial test report

Contents

1. Narrative Summary of Preparations for the Test Programme, Results and Plans for Further Work

Preparations for the test programme envisaged in the original FOCUSS proposal and Deliverable D2 (Appendix 1) involved modifying the existing TERC amine capture plant (ACP) to operate with lean and rich amine storage. A detailed design (Appendix 2) and modified operating methods (Appendix 3) were produced, and their performance was assessed in a HAZOP exercise on 14 June 2023.

Following successful completion of the HAZOP and some resulting minor design modifications, procurement and construction of the additional equipment at TERC took place in the latter part of June, July and early August. A key component of the solvent storage system is a pair of 1m^3 stainless steel Intermediate Bulk Containers (IBCs); AISI 316 stainless steel units are required instead of the standard polythene IBCs to withstand the slightly-elevated flue gas pressure at the base of the absorber column. These stainless IBCs were scheduled for delivery in early August but on 24 July, we were told that “there has been an accident at the facility which has hampered production” and that the units would not be delivered until at least the latter part of August.

Given the FOCUSS timeline and a pre-arranged testing window at TERC for the month of August, it was therefore decided to adapt the FOCUSS solvent storage system design to use the existing ACP reboiler as storage by selectively bypassing the internal weir and so enable the almost complete drainage of the reboiler. This gives a working volume of around 400 litres for absorber performance tests (just over 1 hour of operation) and approximately 100 litres for start-up tests (around 20 minutes of operation from storage). With these capabilities, it was expected that all aspects of the FOCUSS operation could usefully be tested and assessed in an initial phase of 5 days, with the expectation that learnings could then usefully be implemented in modifications and revised planning before the next available TERC test window, in late 2023 or early 2024.

Test performance fully matched these expectations. Over 5 days of testing, all main aspects of FOCUSS operation were demonstrated, generally successfully, but also with indications for areas that could be improved:

- The variation in absorber capture rate with lean solvent flow rate for a fixed flue gas input (the ‘absorber corner’) was demonstrated using stored lean solvent, so with constant lean loading, for three lean loading values, with trends as expected - but absorber settling times were longer than expected (20 minutes at each flow condition) so future operation with larger amounts of solvent storage will be an advantage.

- Stripper start-up without solvent circulation and then switching to circulating operation proved straightforward - but pressure control in the stripper exhibited cyclical instability, so an assessment of lean loading, and hence potentially its control, via the reboiler solvent temperature, proved imprecise. Improved stripper pressure control within the limits of the existing equipment, which had not originally been an area for attention, will therefore be addressed for future tests.

- A start-up sequence with high capture rates at all times was demonstrated, initially using stored lean solvent, then switching to normal cyclical operation, taking solvent from the stripper and finally taking additional lean solvent from the stripper to replace the lean solvent in storage while also maintaining cyclical operation. Periods of operation from/to storage were limited to 20 minutes, but all the principles could be demonstrated. However, it became evident during testing that much better control, both during start-up and throughout operation, could be obtained if a series storage arrangement was implemented with some holdup of both lean and rich solvent in storage at all times. Paradoxically, it used to be thought that this holdup would impair the responsiveness of the system, but these initial tests have shown that this arrangement allows what matters – the achieved CO_2 capture rate and demands on the power plant – to both be managed with the best possible precision. This feature will, therefore, be implemented in future tests on the ACP.

  The revised storage system design for this initial phase, achieved test results, the consequent proposed ACP modifications and planned tests in the next phase of testing (currently envisaged for late 2023 or early 2024) will be described in the following sections of this report.

Figure 1.1 Lean solvent storage tank and reboiler weir bypass in place on TERC ACP

Figure 1.2 Lean storage tanks adjacent to (L to R) Desorber, Absorber 1 and Absorber 2 columns

2. Preparations for the Test Programme and Results

2.1 Revised storage system design

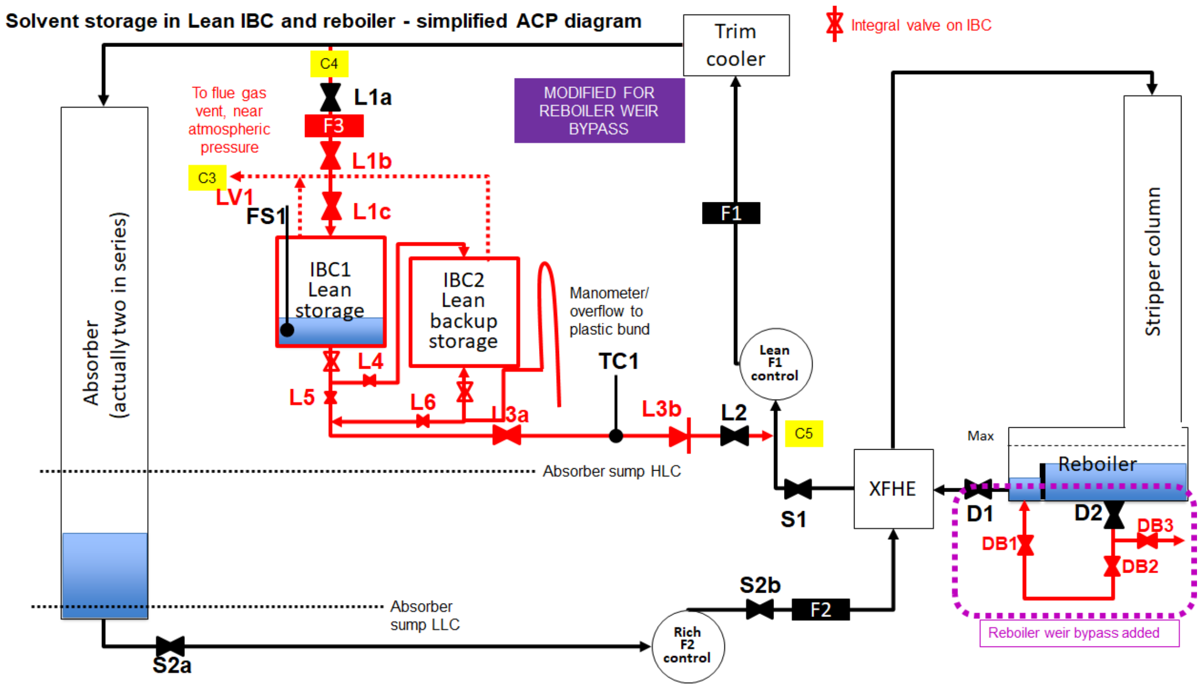


Figure 2.1 Revised solvent storage using Lean IBC and reboiler – simplified diagram

The revised solvent storage arrangements are shown in Figure 2.1. The lean storage system is as designed previously. The maximum rich storage of around 400 litres is effectively the whole reboiler, because a weir bypass line has been added to allow the heating coil region behind the weir to be drained. This bypass is, however, only used when the stripper is depressurised and cooled, an analogous procedure to the normal draining of solvent from the plant. If rich solvent storage is required when the stripper is operating (i.e. for start-up demonstrations), then the weir is placed in operation, and the available volume becomes that between a low-level sump and a high-level sump (which also overtops the weir), i.e. slightly in excess of 100 litres. In both cases, the available solvent volume has already been shown to be able to be accommodated safely in lean and rich storage during the filling process.

The procedures for system filling, absorber corner and start-up tests (including stripper start without circulation) are as follows:

1. Filling

- Fill up the plant with solvent so that the Desorber sump is near HL, Absorber 1 and 2 sumps are near HL, and Lean IBC has ~50 mm of solvent. Transfer some solvent from the Desorber to the Lean IBC1 and reduce the level in Absorber 1 to near low level – this then sets the working level in the Lean IBC1. This still leaves plenty of room in

Lean IBC1 for all of the remaining solvent in the plant but gives a reserve to avoid the Lean Pump sucking dry (because Absorber 1 sump or Desorber sump will reach HL and trip first).

- Lean IBC2 is not expected to be used unless Lean IBC1 is overfilled – which is impossible because of the limited amount of solvent in the system.

2. Absorber Corner Test Operation

a) Run the stripper to get the required lean loading (taking into account the solvent in Lean IBC1). If the weir is overtopped, there may be some mixing, but the Weir Bypass should be isolated and vented as it is not intended to take pressure. The solvent can be circulated lean through Absorber 1 (without flue gas flow) during the leaning phase to facilitate mixing and sampling. (It also proved feasible to use the lean pump to circulate solvent around the stripper/reboiler without going to the absorber, using manual valve adjustments).

b) Shut off reboiler heating, shut off Lean Pump flow to Absorber 1 if in use and get Absorber 1 sump level low.

c) Open the Weir Bypass. Transfer lean solvent to Lean IBC1 via the Lean Pump and the Trim Cooler until just above LL in the Desorber. Stop the Lean Pump. Close off the line to the Lean Pump from the Desorber. Leave the Weir Bypass open if desired so that the Desorber level in the heating coil section can be seen. The Lean Pump can also subsequently be operated to circulate solvent from and to Lean IBC1 if desired to ensure the lean solvent is thoroughly mixed.

d) Start flue gas flow and establish the desired CO_2 concentration.

e) Open feed from Lean IBC1 to the Lean Pump and from the Lean Pump to Absorber 1; feed Absorber 1 at varying flow for the test; use the Rich Pump to maintain a satisfactory level in Absorber 1 sump. Stop just before HL in the Desorber sump, and Absorber 1 sump. This procedure was found in practice to give 60-80 minutes of testing, depending on flow rates.

f) Close and vent the Weir Bypass. Isolate Lean IBC1 connections to plant. Go to a) to lean out the solvent again.

3. Start-up Test Operation

a) Lean out a full solvent inventory to the desired value, as above. Transfer the lean solvent to IBC1 to the point where both the Desorber (with the weir in operation) and Absorber 1 sumps are near LL.

b) Start the flue gas flow and establish the desired CO_2 concentration.

c) Bring the Desorber to operating temperature and pressure without solvent circulation.

d) Open feed from Lean IBC1 to the Lean Pump and from the Lean Pump to Absorber 1; feed Absorber 1 at minimum solvent flow (300 kg/hr) to near HL on Absorber 1.

e) Start the Rich Pump to maintain a satisfactory level in Absorber 1 sump, sending rich solvent to the Desorber. Just before reaching HL in the Desorber sump, open valve D1 to direct lean solvent from the Desorber flow to the lean pump and then close valve L3a to stop lean solvent flow from Lean IBC1. The plant is now operating in normal circulation mode.

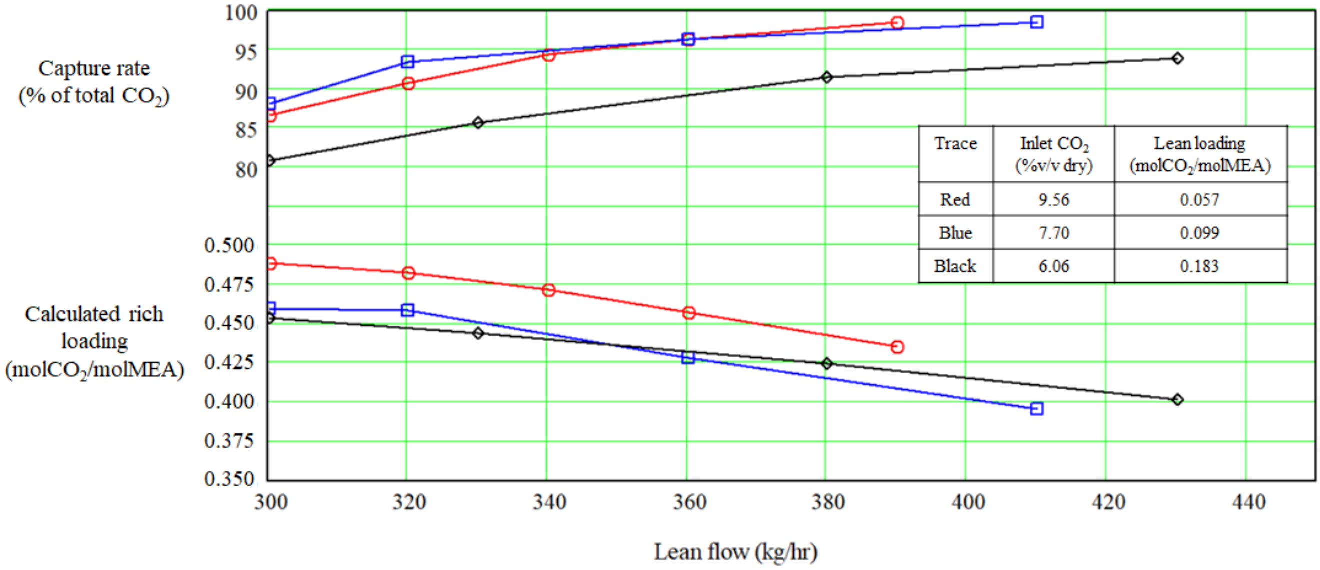
f) To replace the lean solvent, when ready, increase the Lean Pump flow to a higher value (400 kg/hr was found to be sufficient to avoid bubble formation that would interfere with ultrasonic flowmeter F3 operation) and use valve L1c to set the flow to IBC1 at 100 kg/hr. Stop when the level in the Desorber approaches LL. The plant is now operating in normal circulation mode again.

2.2 Absorber corner tests

Three absorber corner tests were undertaken at lean loadings of 0.057, 0.099 and 0.183 molCO_2/mol MEA. In all cases, because of the limited volume of solvent storage available, the lean flow was started at 300 kg/hr, the lowest controllable value, the gas flow was constant at 210 m^3/hr, the highest possible value, and the absorber inlet CO_2 concentration was adjusted to get 80-90% capture. The lean flow was then increased in 20-40 kg/hr increments with 10-15 minutes dwell time at each flow, determined by inspection of the operating parameters such as CO_2 and water concentrations in the exiting flue gas and absorber temperature profiles. An example of ACP measurements during an absorber corner test is shown in Figure 2.3 overleaf, with the parameters and averaging periods for the other corner tests shown in full in Appendix 3. Absorber corner plots for the three runs are shown in Figure 2.2 below.

Corner plot trends are generally as predicted (see Appendix 1), although lack of solvent storage has limited the extent to which the asymptotic approach to the lean equilibrium capture limit at higher flow rates can be explored. This is not, however, a region where commercial plants are likely to operate due to excessive solvent regeneration energy requirements.

Based on these results, satisfactory test performance with a larger solvent storage capacity (anticipated to be approximately 1.5 m^3 vs. 0.45 m^3 in this test phase) is confidently anticipated. This will allow longer periods for stabilisation (e.g. 30 mins vs. 10-20 mins) at each lean solvent flow rate, a wider range of flow rates and hence five or more test points for each corner test.



Trace	Inlet CO_2 (%v/v dry)	Lean loading ($molCO_2/molMEA$)
Red	9.56	0.057
Blue	7.70	0.099
Black	6.06	0.183

Figure 2.2 Corner plot test results from this initial FOCUSS test phase

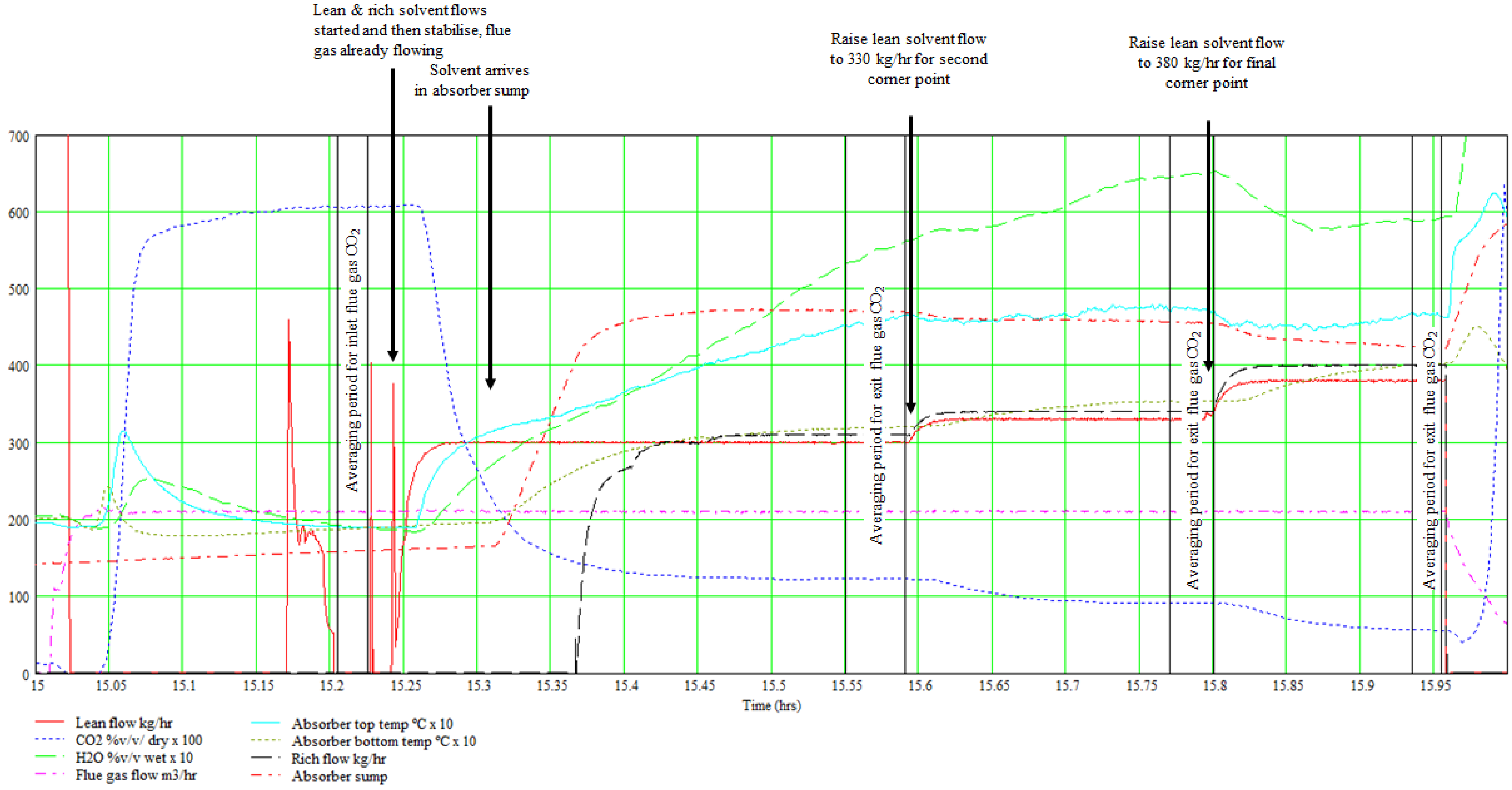


Figure 2.3 Example absorber corner test run showing parameter variation over time and averaging periods for gas analyses

(Lean loading 0.183 molCO_2/molMEA)

2.3 Start-up with solvent storage used to maintain high capture rates

Figure 2.4 below shows a start-up sequence that illustrates the main principles of using solvent storage to achieve high capture rates throughout operation but in which, because of the limited rich solvent storage available, there was a gas-first start rather than a liquid-first start (where, obviously, only minimal CO_2 emissions will occur) and also there was rich solvent going to the stripper for storage from the start of the test (i.e. the stripper received solvent earlier than would have been expected if separate rich storage had been available).

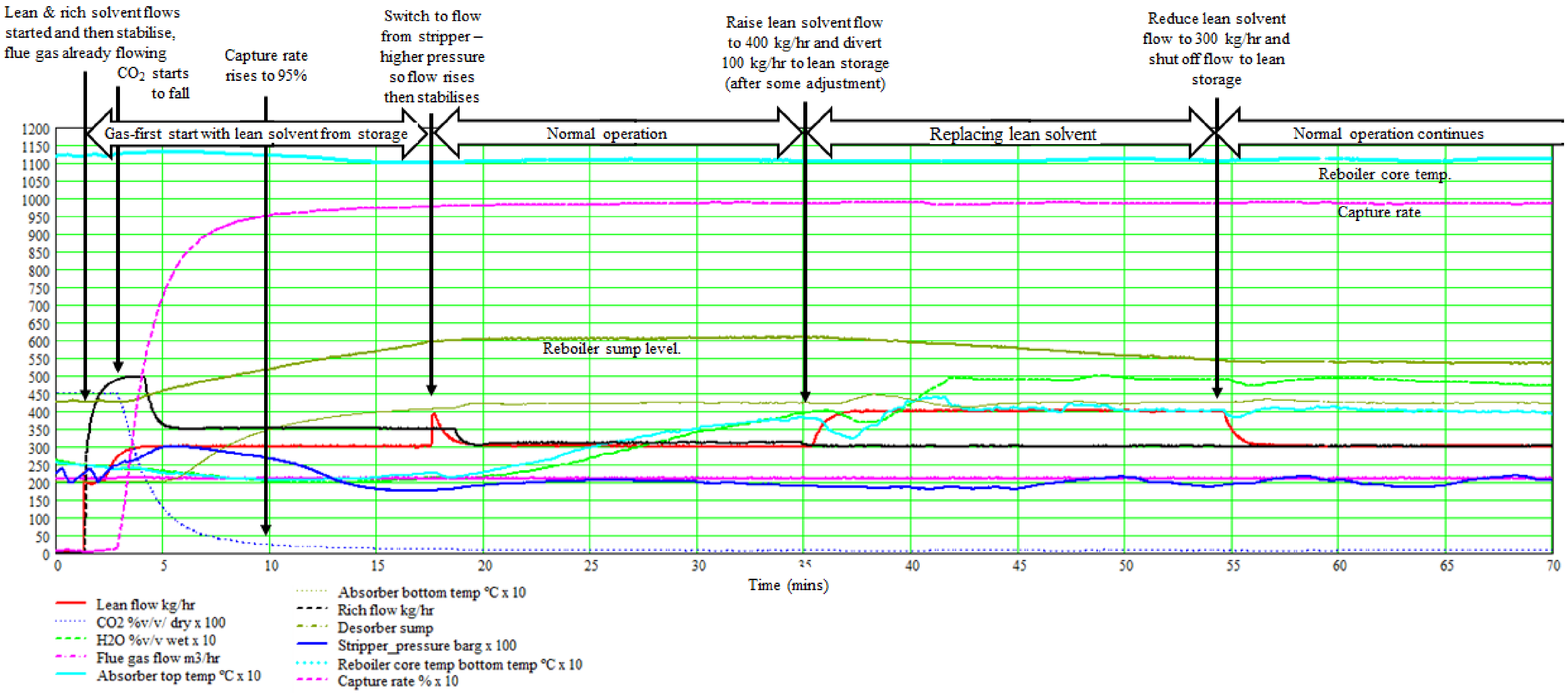


Figure 2.4 Demonstration PCC plant start-up sequence using external lean solvent storage and low-to-high level capacity in the kettle reboiler as corresponding rich solvent storage

3. Plans for Further Test Work

3.1 Revised solvent storage system design

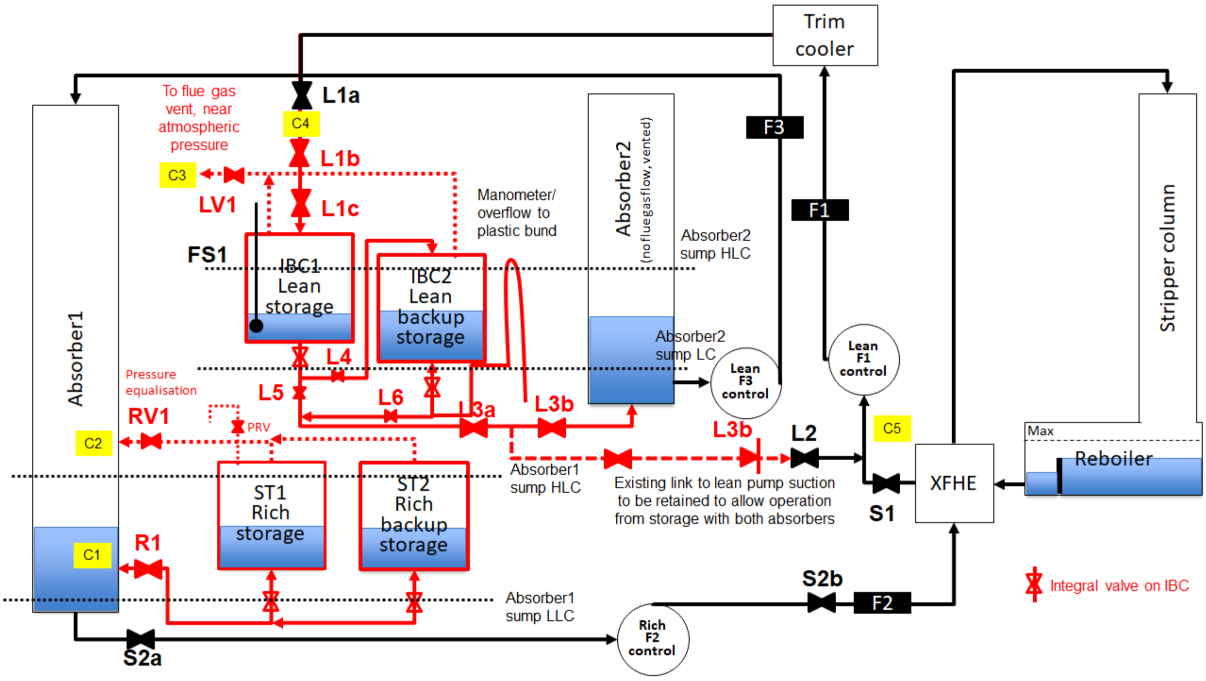


Figure 2.1 Revised solvent storage using Lean IBC and reboiler – simplified diagram

Building on the experience of this initial testing phase, a revised solvent storage arrangement has been proposed, and final design and implementation are expected to take place over the next 2-3 months. The principal feature of the modification is to use the sump, solvent pump and flow controller for Absorber 2 to take lean solvent from storage to Absorber 1 in parallel with lean solvent addition to the lean storage if desired. This modification, in addition to simplifying start-up arrangements, allows fully-independent operation of the absorber and stripper, respectively and hence their independent performance optimisation, within the limits of the plant and available storage. Because of the inherent flexibility of the existing ACP design, this modification can be undertaken mainly using existing features, simply by connecting the lean storage IBCs to the sump of Absorber 2 with a gravity flow arrangement (but note the existing connection from lean storage to the lean pump suction will be retained to allow series operation of both absorbers from storage). Since either lean or rich solvent storage can, alone, accommodate all the available solvent that can be drained from the system, and additionally, all units are protected by existing high/low absorber sump level trips, this arrangement is intrinsically safe.

In addition, the following minor plant modifications would facilitate FOCUSS operations:

i. Put insulating lagging on the absorbers (particularly Absorber 1)
ii. Optimise pressure control on the stripper
iii. Add the capability to specify a fixed reboiler heat input

3.2 Absorber and stripper control enabled by new storage configuration

a) Absorber control features

The main difference with the new arrangements for absorber control is on start-up, which now involves no change in lean solvent source, i.e. the lean solvent always comes from the lean storage tank(s). This will give an inherently seamless transition from operation when the stripper is heating up and not exporting lean solvent to when it comes into operation.

In addition, under all operating conditions, changes in lean loading are likely to be extremely slow since they are buffered by the volume of stored solvent and mixing in the lean storage tanks, so precise control of the absorber to match liquid and gas flows to give the desired capture rate is likely to be greatly facilitated.

b) Stripper control features

The principal feature of the new solvent storage arrangement is that it removes the requirement for the stripper to provide the continuous, steady lean solvent flow that is needed in the absorber to capture CO_2 at high rates. However, obviously, it must meet the average required flow over the long term operation of the plant. Crucially, this decoupling means that if the lean solvent is not at the required loading, then lean flow out of the stripper can be stopped or reduced while other stripper operating parameters (i.e. rich solvent flow in, heat input, pressure) are adjusted to correct the discrepancy.

3.3 Future test plans

The basic FOCUSS operating principles have been demonstrated successfully. The objective now is to refine the methods to give better results and undertake the most representative demonstrations feasible within the TERC ACP's limits.

The next test window is anticipated to be in late 2023 or early 2024, allowing time for the stainless IBCs to be installed and the other modifications to be implemented and tested. The next test phase, anticipated to be a further five days, will then be able to undertake the following tests:

i. Absorber corner tests with a high degree of confidence in the procedures and results based on this initial phase (2 days)
ii. Stripper operating method tests (2 days – using solvent from corner tests)
iii. Start-up demonstration, cold and hot start, again with a high degree of confidence in the procedures and results based on this initial phase (1 day)

The final test window, expected to be ten days in mid-2024, may be modified to take into account further learnings, but is expected to include the following:

i. Stripper inflection point (minimum energy) operation at a range of pressures (ideally higher pressures with a new reboiler heater capable of higher temperatures)
ii. Absorber performance tests from storage using the full 12 m of packing in Absorbers 1 and 2 to give greater confidence in modelling predictions, with and without flue gas water saturation in the DCC
iii. Demonstration of final start-up control methods for cold and hot starts
iv. Demonstration of long-term operation with independent control of absorber and stripper operation, with artificial adjustment of flue gas and other boundary parameters to represent typical variations over time that might be encountered in practice

4. Dissemination and Impact Activities

Updates on FOCUSS, including results from this initial test phase, will be disseminated in the following ways over the rest of 2023:

- Included in a poster on 'Effective amine post-combustion CO_2 capture from power and industry' at the UKCCSRC conference on 6-7 September https://ukccsrc.ac.uk/event/ukccsrc-knowledge-exchange-conference-2023/

- Update in the FOCUSS IEG webinar on 18 September

- FOCUSS presentation at the IEAGHG PCCC 7 conference on 25-27 September https://ieaghg.org/conferences/2-uncategorised/1060-pccc-7

- One or more LinkedIn articles

Appendix 1. Proposed Test Programme from Proposal and D2

The italicised text below is quoted directly from D2.

2.1 Test programme as envisaged in the proposal

WP4: TERC test programme (lead TERC)

Advantage will be taken of the ability to store solvent for a number of hours of operation to accelerate steady-state tests using this approach for absorber and stripper testing, with the gas mixing skid also allowing rapid changes in CO2 concentration. This flexibility will allow a comprehensive dataset to be collected for initial modelling and engineering assessments and to inform the design and execution of future engineering phases. The outline test plan comprises two periods:

Period 1(2 weeks): storage tests, baseline, lean sensitivity, 95-99% capture tests

Period 2(2 weeks): 95-99% capture tests, start-up/transition events using solvent storage

The 4-week test campaign is intended to fit within the wider window allocated for FOCUSS testing, which includes contingency to cover any outages.

This approach will be implemented as largely as planned, with conditions selected based on learning from the PCC-CARER tests, with the following objectives (see Section 4 for storage configuration descriptions and outline operating procedures):

1) *SUSD operation from storage demonstration*
2) *Dual storage for testing demonstration, with objectives for stripper and absorber as follows:*
    a) *Stripper – investigate the change in inflection point lean loading with pressure at constant rich loading*
    b) *Absorber – investigate capture level as a function of solvent flow rate at constant lean loading*

The total test period in this first campaign is 10 x 8-hour days. Although SUSD operation demonstration is the main objective for this campaign, the dual storage tests will start first, to help commission operation from storage and to inform what are 'normal' operating conditions for the SUSD tests. Test activities below are therefore described in this order.

2.2 Planned dual storage test programme – 5 days

Artificial flue gas mixtures of CO_2 in air will be used. As noted in Section 2, the maximum gas flow achievable in the ACP at present is 210Nm^3/hr and the minimum lean solvent flow rate is 300 kg/hr. This means that, for absorber tests with a lean *loading in the region of 0.1 molCO_2/molMEA and a rich loading of 0.45, the minimum flue gas CO_2 content is constrained to ~7.5% v/v (i.e. the L/G cannot be made low enough for ~ 4%v/v CO_2).*

For stripper testing, where high and approximately constant (between tests) rich loadings are required the possibility of sparging pure CO_2 into the rich storage tanks to raise the rich loading if required will also be investigated.

2.2.1 Dual storage testing – absorber – 5 days (with stripper tests)

These tests will be conducted with constant lean loadings using a single well-mixed IBC. With a working IBC capacity range estimated at ~ 700 litres and a minimum solvent flow of the order of 300 kg/hr then approximately two hours of operation are theoretically feasible, with some allowance for increased solvent flows for testing purposes. The time for the absorber performance to stabilise for changes in liquid flow rate, gas flow rate/CO_2 concentration etc. will need to be determined, but may be 20 minutes or less, giving 6 data points or more. It remains to be determined whether or not two sets of runs from storage are feasible in an 8 hour day, allowing for analysis and switching time etc. Time for commissioning is also uncertain.

It is envisaged that each run from storage will be intended to map out a capture performance curve as a function of solvent flow at fixed lean loading, shown in Figure 2.1. At each point the principal measurements are inlet and exit flue gas flows and concentrations, solvent flow rate and rich loading. Solvent samples will be retained and it will also be possible to review loading data in the future as additional tests become available.

Expected capture levels will be in the range 95-99 % with variable lean loading and solvent flow rates that optimise rich loading and capture level (i.e. not too little and not too much solvent flow), with particular attention to the effect of lean loading changes in the range 0.15 – 0.25 molCO_2/molMEA.

As shown in Figure 2.1 there is expected to be a characteristic solvent flow rate for a particular lean loading and flue gas flow and CO2 concentration. Too low solvent flow and there not enough solvent capacity to achieve a high capture level, too much solvent and the capture level will increase only slowly while rich loading will decrease proportionately. The key is the turning point in flow vs capture graph (note this process would be impossible without solvent storage because the change in flow through the stripper would also cause changes in the lean loading).

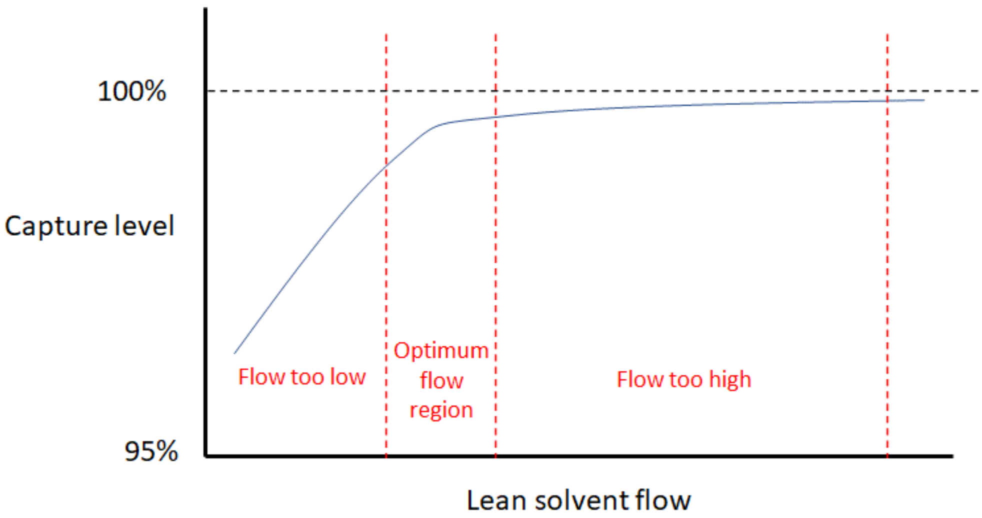


Figure 2.1: Expected variation in capture level with constant lean loading

The envisaged absorber test matrix is as follows:

Flue gas CO_2 concentration	*7.5% v/v dry*
Approximate lean loadings	*0.09, 0.12, 0.15, 0.2, 0.25 molCO_2/molMEA*
Absorber packing heights	*12 m (dual absorbers), plus optionally, if time permits, 6 m (single absorber)*

This gives a maximum of 10 runs using storage, which assumes that simultaneous absorber and stripper operation from (different) solvent storage proves feasible (both operationally and that suitable lean and rich loadings can be achieved for complementary testing) and that two runs can be undertaken per day.

2.2.1 Dual storage testing – stripper – 5 days (with absorber tests)

The objective for the stripper tests is to investigate the relationship between lean loading and stripper performance at a range of pressures, and in particular to see if experimental results confirm the expectation that the corresponding lean loading at the inflection point falls with increasing stripper pressure. As noted above, the inflection point in stripper operation will be inferred from column temperature distribution as well as from measured SRD, noting that the latter also includes a significant heat loss component in the small TERC ACP rig.

The stripper tests will use rich solvent from an IBC at a fixed rich loading. In a commercial plant with a fixed flue gas flow rate the CO_2 release rate in the stripper would be approximately constant, so the solvent flow rate would be increased as the lean loading increase and vice-versa. In these tests, with limited stored solvent available, the flow rate will initially be maintained at a constant, low, value (e.g. 100 - 300 kg/hr), with a limited number of points at higher lean loadings (and hence higher flow rates in reality) being checked at a higher flow rate.

The stripper pressure will be maintained at a fixed value, but the reboiler temperatures will increase slightly as the lean loading is decreased. Because of the thermal inertia of the reboiler contents the time to stabilise is uncertain, possibly of the order of 30 minutes to one hour. If only 2-4 points are possible with an IBC of stored rich solvent then a clear delineation of the inflection point may not be feasible *in a single run and multiple IBCs will have to be used, raising the complication of slightly different rich loadings. As noted, CO_2 sparging will be investigated as a means of adjusting the rich loading if required.*

The lean loadings produced in the above process will also tend to span a range, possibly making it difficult to achieve low lean loadings after mixing. Special regeneration stripper runs without any particular test value may therefore need to be undertaken to accommodate absorber tests with lower lean loadings. CO_2 sparging could, however, possibly be used to increase lean loading if the resulting lean loading was too low for the proposed absorber tests.

It is tentatively assumed that an average of one stripper pressure series will be feasible approximately every two days, allowing two or three pressures to be investigated. Allowable pressures for a full range of loadings will be determined by the heating unit temperature limit. Based on PCC-CARER test experience (see Figure 3.10) pressures would need to be 1.2, 1.3 and 1.4 bar with the current unit. All tests would be undertaken at the minimum solvent flow rate of 300 kg/hr, with at least one higher flow rate, e.g. 600 kg/hr, used at a higher loading value to verify insensitivity to mass transfer characteristics in the stripper column (as suggested by the similarity between 20 m and 40 m trends in e.g. Figure 2.3).

The envisaged test matrix is therefore as follows:

Rich solvent loading	*0.4 – 0.45 $molCO_2/molMEA$ (tighter range if feasible)*
Solvent flow rate	*300 kg/hr, plus higher flow for at least one lean loading per pressure*
Stripper pressure	*1.2 and 1.4 bara plus 1.3 bara if time permits*
	(TBC, depending on heater)

2.3 Planned SUSD test programme – 5 days

Five days testing are allowed for this programme. 'Normal' operating conditions will be selected based on the results of the dual storage programme and will be aimed to give a capture level of approximately 95% or higher for approximately 7.5% v/v CO_2 synthetic flue gas at a solvent flow rate somewhat in excess of the minimum, to allow scope for control.

The key issues for testing are thought to be associated with the stripper rather than the absorber (and absorber operation from storage will anyway be covered as part of the absorber dual storage tests above) and centre around the transition from isolated heating to normal operation and the somewhat similar issue of keeping product lean loadings at target values without excessive energy inputs when rich solvent flows increase or decrease as stored solvent is regenerated.

To a very large extent the stripper behaviour under these conditions will be a function of stripper configuration and control methods. The ACP stripper has a large kettle reboiler in the base with a significant solvent inventory, with a minimum volume of approximately 300 litres held behind a weir to ensure the heating coils are covered *and a maximum capacity of approximately 500 litres. The pressurised hot water (PHW) heater is controlled by specifying the required water temperature at exit from the heater, with currently no option to control the power input (other than using a temperature controller set-point that gives maximum power, as was done for PCC-CARER Runs 1-8).*

Qualitatively, the ways that conditions in the stripper column respond to solvent flow changes are, however, expected to be generally relevant to any stripper operation while fundamental VLE relationships are, of course, universal. Based on modelling studies it appears that the key factors in determining lean loading are:

a) the controlled exit pressure from the stripper and, to a lesser extent, the pressure drop in the column etc. to the point where final CO_2 release takes place before the solvent leaves the stripper, and
b) the temperature to which the solvent is heated at that point of final CO_2 release.

With the ACP kettle reboiler in normal operation exiting lean solvent falls over the weir from the heating coil area, where it is presumably well-mixed and at a uniform temperature and surface pressure. Loading will be determined by the VLE, with the bulk temperature a critical variable, although cyclical oscillations in the controlled pressure about the set point (see Figure 3.4) also have to be taken into account. The PHW temperature controller will, in principle, act to maintain the reboiler temperature constant, but will have response lags and, in any case, the effect is limited by the maximum power available.

Stripper tests are constrained by cooling times (for cold starts) and the amount of stored solvent (IBCs may be combined for $2m^3$ nominal capacity to allow longer tests), also the time take to reload the solvent with CO_2. The cold start heating period, is however, going to be similar in all cases and need not be repeated once the stripper is hot.

The main tests will be:

a) initiating rich solvent flow with a hot stripper with no rich solvent flow

b) increasing rich solvent flow from a steady state value

c) decreasing rich solvent flow to a steady state value

d) shutting down the stripper

The envisaged test programme is:

Phase 1: Cold start, investigation of optimum approach to initiate flow from zero (rate of flow increase, effect of increasing PHW set-point before initiation, effect of over-pressurising stripper before initiation and then depressurising to give thermal reserve. Operation from storage. Provisionally 2 days.

Phase 2: Investigation of optimum approach to increase/decrease solvent flow from steady state value (rate of flow increase, effect of increasing/decreasing PHW set-point before change). Operation from storage and possibly also with the absorber adjusted to give well-loaded solvent. Provisionally 1 day.

Phase 3: Integrated operation with cold start, operation from storage, transition to steady state operation, rich solvent flow increase to regenerate stored lean, shut-down. Optionally a second cycle with hot start in the same day if time allows. Provisionally 2 days.

Appendix 2. Description of Terc Amine Capture Plant (ACP)

The pilot scale CO_2 capture plant at TERC is capable of capturing 1tpd CO_2 based on 200 Nm^3/h gas flow having 15% CO_2 i.e. the plant is designed for coal combustion flue gases. The plant is integrated with site combustion facilities including: Grate Boiler/Waste to Energy plant; Gasifier CHP; Biodiesel CHP, Gas Turbine CHP and a visiting/future rigs. It is designed to scrub 100-250 Nm^3/h of flue/process gas with solvent flows of 300-1600 kg/h based on current packing. The plant can also be fed from a dedicated synthetic gas mixing skid comprising 3 bulk gas streams: CO_2, N_2 and Air, each of 6-300Nm^3/h flow rage and a trace gas (NO_2, SO_2) injection capability; this enables the simulation or modulation of a range of combustion/process gases. The plant is shown in Figure A2.1. Equipment specifications are given in Table A2.1. The plant has a full absorption and desorption cycle and is equipped with two absorber vessels that can be connected in series (only one was used in the FOCUSS tests to avoid excessive and unrealistic absorber hold-up times), a stripper, a reboiler, a cross exchanger, a carbon filter and a water wash. The plant also has a gas pre-treatment section which can be used either as a Flue Gas Desulphurisation (FGD) unit or a Direct Contact Cooler (DCC). The plant has recently been upgraded to including gas humidification control in the DCC. However, during these tests the FG/DCC was bypassed.

Figure 8: TERC CO_2 capture plant

Two absorber vessels are installed in series to increase residence time and contact between liquid and gas. Each of the absorbers is equipped with two beds of Flexipac 350X structured packing, 3m each. Total packed height, therefore, is 4 beds of 3 m each, so totalling 12 m, with liquid re-distribution at each bed. The stripper is packed with 7 m of IMTP25 random packing. The absorbers have 12 temperature measurement points each for temperature profiling.

Stripping is performed in the stripper and reboiler. The stripper is a 0.3 m diameter column packed with IMTP25 random packing. The reboiler is a shell and tube heat exchanger. Pressurized hot water (PHW) generated by electrical heating is supplied on the tube side of the reboiler while solvent stays on the shell side.

The PHW has a bypass to control the flow rate through the reboiler or to bypass it. A pneumatically driven 3-way valve is used for this purpose. The energy used for stripping is calculated by measuring the inlet and outlet temperatures and the flow rate of the PHW. Stripper pressure is controlled automatically to a user defined set point.

The CO_2 product stream leaving the top of the stripper is passed through a condenser to remove steam and solvent vapours. The condensed liquid is separated from the gas in a reflux drum and is sent back to the stripper through a U-seal mechanism, while CO_2 is exhausted to atmosphere after analysis.

A blower is used to drive the gas through the plant. For this test campaign, air with CO_2 injection, rather than real flue gas, was used, to give controlled CO_2 levels.

CO_2 flow was measured by thermal mass flow meters, while the flow rate of gas into the absorber was measured by a pitot type flow meter. Gas composition for mass balance calculations was measured at the inlet and outlet of the absorber, along with temperature and pressure.

Table A2.1 Absorber and stripper specifications

Specifications	Absorber	Stripper	Water wash
Diameter (mm)	250	300	300
Packing name	Flexipak 350X	IMTP25	IMTP25
Packing type	Structured	Random	Random
Packing height (m)	12	7.5	7.5
Packed beds	4	1	1
Temperature measurements	24	9	-

Table A2.2 Process and analytical measurements

Analysis	Detail
Main Process parameters	• Gas inlet flow, temperature and pressure • Interstage gas temperatures and pressures • Absorber 1 &2 and desorbed temperature profiles and pressure drops • Desorber pressure (reflux condenser) and CO2 product flow • Liquid flows, temperatures pressures and densities • Reboiler hot water flow; inlet, outlet, core temperature; supply pressure
Gas analysis	Multipoint sampling and analysis by Gasmet FTIR: 1. Absorber 1 column inlet, 2. Absorber 2 column inlet, 3. Water wash column inlet, 4. Water wash outlet; 5. Desorber outlet after reflux condenser
Liquid titrations	Mettler Toledo auto titrator 1. Fast loop sampling from Abs 1 (Rich), Abs 2 (Semi-rich) and Desorber (Lean) 2. MEA solvent concentration 3. CO2 concentration and loading
Dissolved oxygen analysis	Jumo online oxygen analysis 1. Lean (desorber outlet) 2. Semi-rich (absorber 2 outlet) 3. Rich (absorber 1 outlet)
Iron analysis	Analysis on • Lean (desorber outlet)

Process and analytical measurements are described in Table A2.2. Gas analysis can be performed at 6 different locations in the plant. Sampling lines are located at the FGD inlet, Absorber 1 inlet, Absorber 2 inlet, Water wash inlet and outlet, and Stripper outlet.

The gas samples are extracted from the plant using isokinetic sampling probes and routed to the FTIR through heated filters, heated sampling lines and a heated cabinet housing solenoid for sample switching. The entire sampling system is heated up to 180ºC to avoid condensation.

A Gasmet DX4000 FTIR is used for gas analysis, which sequentially tests samples from each of the locations. The sequence and sampling time is user defined and can be changed in the FTIR software as and when required. For these tests, gas compositions at Absorber 1 inlet (GSP02) and Absorber 2 outlet (GSP06) were used for overall capture efficiency calculations.

Solvent analysis are performed by an in-line and offline measurements. For online analysis, Mettler Toledo auto-titrator shown in Figure A2.2 is used. The apparatus was acquired to be run over the weekends remotely and keep weekend samples for analysis. However, the apparatus did not work as intended and some of the samples over the weekend could not be collected. The apparatus collects three solvent samples (rich, lean and semi-rich). The fast sampling closed loop keeps a small bleed stream of solvent in circulation in respective stream and peristatic pumps are used to acquire samples when needed. The auto-titrator performs titrations on the three samples for solvent concentration and CO2 loading analysis. Off line measurements were performed for Fe analysis. Lean samples collected by the auto-titrator can be used for Fe analysis using colorimetric method using the apparatus shown in Figure A2.3.

Figure A2.2 Mettler Toledo auto-titrator

Figure A2.3 Fe measurement apparatus

Appendix 3. Absorber Corner Test Data not Included in Main Reports

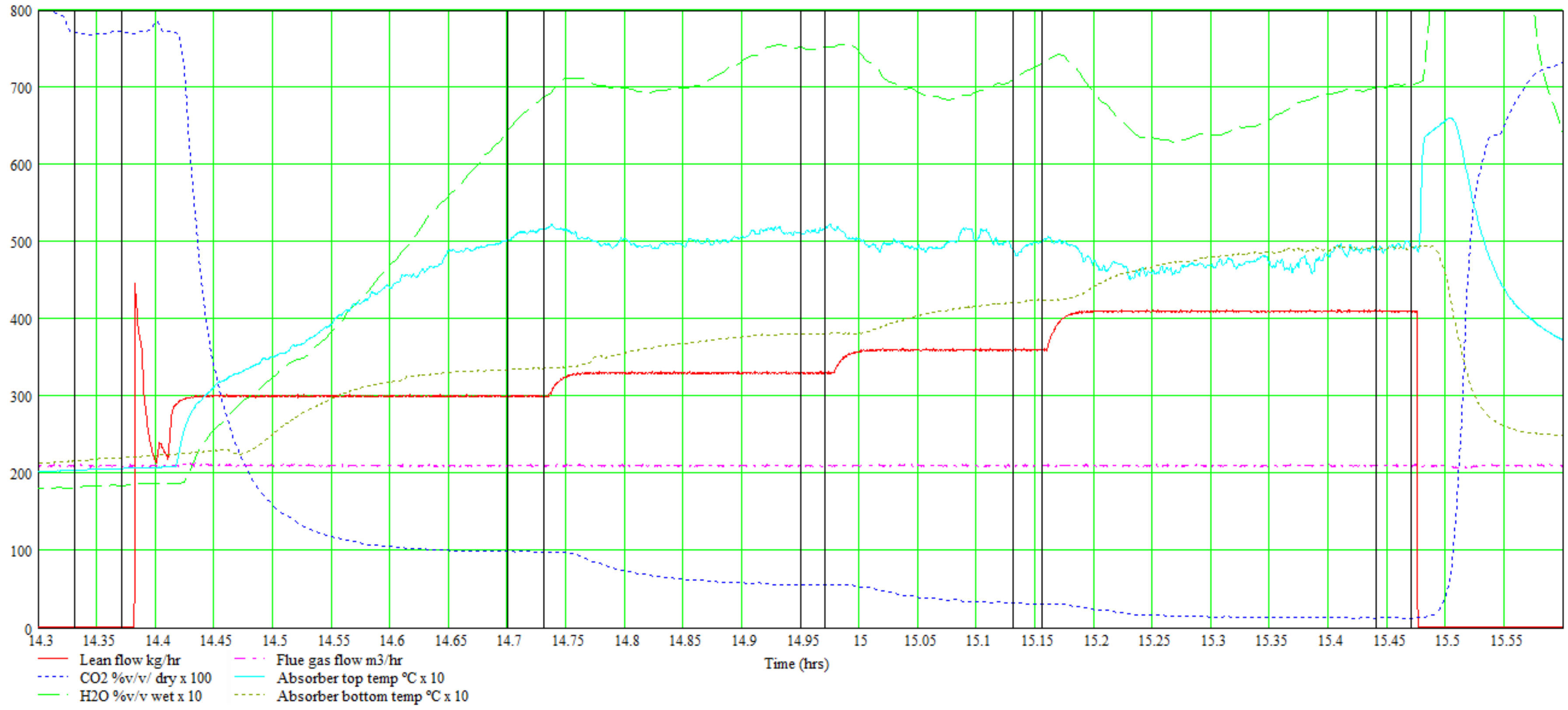


Figure A2.1 Absorber corner test results for 0.099 molCO2/molMEA lean loading and 7.70% v/v dry CO_2 in the flue gas to the absorber

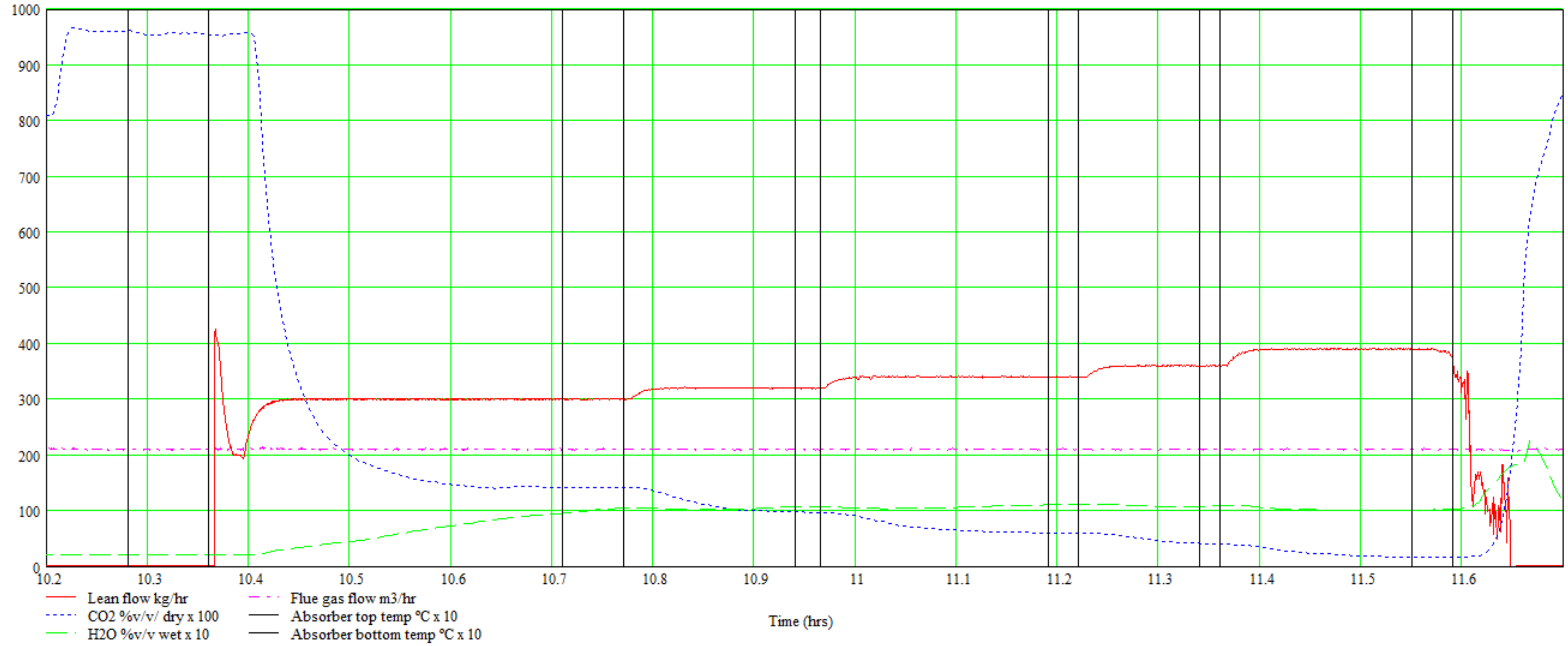


Figure A2.2 Absorber corner test results for 0.057 molCO2/molMEA lean loading and 9.56% v/v dry CO_2 in the flue gas to the absorber

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