FICHTNER
Consulting Engineers Limited

Runcorn CC facility

Viridor Runcorn CCS Ltd

Schedule 5 Response

ENGINEERING + CONSULTING

Document approval

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Contents

1 Multi operator installation

1. **Provide a process flow which clearly defines those parts of the process which the CC facility is responsible for and those which are the responsibility of the ERF.**

   A responsibilities/interface matrix setting out the responsibilities for each of the Operator's is provided in Appendix A.

2. **Confirm which facility will be responsible for the back pressure turbine and show in the process flow how the back pressure turbine links to the carbon capture facility.**

   The Viridor Runcorn CCS Ltd will be the 'Operator' of the back pressure turbine, and will utilise high pressure steam which is supplied by Lines 3 and 4 of the ERF (operated by Viridor Energy Ltd) to generate power and provide medium and low pressure steam which will be utilised within the CC facility.

2 Air Quality Assessment

3. **Provide a dispersion modelling assessment that includes assessment of emissions vented from the new emission point in the absorber stack if the CC facility is not available.**

When the CC facility is not available the emissions will be vented via the existing ERF stack. Therefore, there will be no emissions from the new emission point (absorber stack) if the CC facility is not available.

4. **Provide the following clarifications to explain the CO2 venting release scenario and ADMS modelling to represent worst-case impacts**
   a. **Justify the suitability of the source terms (inputs to the ADMS model), explain how the exhaust temperature, velocity and mass emissions were estimated and discuss their potential ranges/variability. In your justification, please also include the process CO2 pressure and temperature conditions and CO2 phase(s).**
   b. **Consider the previous point to justify that ADMS is a suitable modelling software to mimic CO2 releases and predict impacts at locations of public exposure.**

The inputs into the ADMS software were obtained using the Aspen Flare System Analyser (AFSA) (v14) to size the plant venting header(s) and stack. The AFSA software package is an established flare/vent simulation and sizing system that conforms to industry design guide/standards (API etc.) and using a combination of vapour liquid equilibrium (VLE)/thermodynamic modelling (Peng Robinson methodology) and hydraulic calculations (Beggs and Brill methodology) to model the gas vent/flare conditions and properties (velocity, temperature, pressure, phase etc.).

The methods used within the AFSA software package are widely used in process simulations and are applicable to many systems including gaseous CO_2.

Key inputs into the AFSA model included the following:

- CO_2 inlet conditions (composition, temperature, pressure);
- CO_2 vent inventory;
- Vent pipework length/elevation estimates;
- Vent pipework Heat transfer assumptions; and
- Vent pipework maximum velocity and momentum constraints.

Key outputs from the AFSA model included:

- Outlet CO_2 vent conditions (flowrate, temperature, pressure, phase etc.);
- Outlet CO_2 vent velocity; and
- Vent pipework sizes.

CO_2 vent flowrate variability depends on assumed CO_2 inventory to be vented from system. For the CC facility, the worst case scenario vent flowrate was assumed (full process flow vent) to be the basis of dispersion analysis. Other venting scenarios such as maintenance and process upset are considered to be less than the full process flowrate.

Variability in CO_2 temperature will depend on the pressure drop and heat transfer across the vent pipework.

To simulate the worst case scenario for CO_2 temperature drop and dispersion, pipework length(s) were conservatively estimated based on the layout of the CC facility, and it was assumed that there would not be any heat transfer to the pipework. Including heat transfer into the pipework would increase the temperature of the CO_2 gas and enhance dispersion from the stack.

At standard temperature and pressure CO_2 is denser than air. Vented CO_2 will be released from the vent stack at a height of 110 m. The CO_2 will be in the gas phase and at ambient pressure at the point of release from the stack. A dense gas will sink towards the ground but as it does it will become less dense as it travels and mixes as air is entrained. As such, a gas that is categorised as “dense” at a release, i.e. initially has negative buoyancy, can become neutrally buoyant (and no longer act like a dense gas) when or before it reaches the ground.

Dense gas models tend to specialise in simulating the slumping and ground-level spreading behaviour of dense gases released at or close to ground level and are not generally specialised in modelling the initial dispersion of elevated releases from very tall stacks. ADMS 6 includes algorithms that monitor the plume behaviour as it disperses, and to determine whether the plume is too dense to continue modelling. The plume is ‘too dense’ when the plume spread is determined by gravity effects instead of atmospheric mixing at the point when the plume reaches ground level. The model determines this to be the case if all of the following three conditions are met:

1. The Richardson number (the ratio of buoyancy to shear) is greater than 10;
2. The percentage difference in density between the plume and the ambient air > 0.33%; and
3. The plume reaches the ground less than 250 m from the source.

If any of these conditions are met, the model will fail to run and will return an error message. Given that the model has run successfully, it is considered that the dispersion would be determined by the buoyancy of the plume and atmospheric conditions rather than gravity effects. Therefore, this demonstrates that it is appropriate to use ADMS 6 to model the potential worst-case CO_2 impacts from the Facility.

3 CO2 management, containment, and fugitive emissions management

5. **Provide the following information regarding containment of captured CO2:**
   1. **Maximum inventory of CO2 on-site at any one time.**
   2. **Description of CO2 containment arrangements pre and post compression.**
   3. **Site plan showing locations of CO2 containment pipelines/other vessels and vent stacks (see also question 14).**

Management of the captured CO2 from the process is directly associated with operation of the carbon capture activity so will be included in the permit. The inventory includes CO2 in pipelines and manifolds as well as any stored. Further information is required.

a. Maximum CO_2 Inventory

Carbon dioxide inventory will be present in the CCP in the following forms:

- As a constituent of the flue gas from the ERF;
- Absorbed in the MEA amine solution;
- As a low pressure gas from the stripping; and
- As a high pressure gas from the compression.

Based on a basic equipment and pipe sizing, approximate gas and liquid CO_2 inventories present in the CCP are shown in Table 1 & 2. This estimate is very preliminary and is subject to change in the in next project phase when detailed plant equipment and piping design data should become available.

Table 1: Free Gas CO_2 Inventory Estimate

Containment Area	**CC process stage**	**CO_2 Inventory (kg)**
CO_2 Removal	Inlet Flue Gas Duct	112
	Direct Contact Cooler Vessel	192
	Stripper Colum	1253
	Stripper Reflux Drum	16
Compression	Compression Piping	2101
	Compression Vessels	1195
Dehydration/Deoxygenation	Dehydration Package	722
	Deoxygenation Package	854
Metering	CO_2 Metering Package	44
Total		**6489**

Table 2: Amine Absorbed CO_2 Inventory Estimate

Containment Area	CCP System	CO_2 Inventory (kg)
CO_2 Removal	Stripper Column	1736
	Rich Amine Piping	2091
Total		**3827**

b. CO_2 Containment Arrangement

A Site Plan showing the location of the CO_2 containment facilities is provided in Appendix D. As shown in the plan, the plant is geographically separated into process plant areas as follows:

- CO_2 Removal;
- Compression;
- Dehydration/Deoxygenation Plant; and
- Metering.

The plant areas will be physically separated to contain the CO_2 and prevent significant health and safety issues in the event of an uncontrolled release of CO_2. Emergency shutdown valves will be suitably located to enable each plant area to be isolated on a signal from the shutdown logic. This will ensure containment of the pressurised process fluids in a particular process plant area. The CO_2 inventory in each of plant area is provided in Table 1 and Table 2.

Safeguards and Mitigations Against CO_2 Loss of Containment

Loss of CO_2 containment within the CC facility can occur, but is not limited to, the following scenarios:

- Corrosion leading to containment failure/rupture;
- Low temperature embrittlement leading to containment failure/rupture;
- Overpressure leading to containment failure/rupture;
- Inappropriate plant material/components;
- Inappropriate operator action or maintenance activity; and
- Process control fault.

As part of the containment arrangement of CO_2 present in the plant, the following measures are proposed to be implemented:

- **Material selection:** suitable material grades designed to appropriate codes/standards will be selected based on the operating conditions for both pre-compression and post-compression systems. This includes ducting, piping, vessels, internals, seals etc.
- **Corrosion management:** free water removal by dehydration system for CO_2 containment piping and equipment.
- **Overpressure system:** pre/post-compression systems to be equipped with appropriately designed overpressure devices (PSVs, rupture discs) which will route release to the safe place (stack).
- **Plant inventory segregation:** appropriately specified shutdown valves will be strategically placed between different plant containment areas to minimise any CO_2 release as result of loss of containment.
- **Emergency shutdown:** appropriate plant shutdown levels (area/unit etc. as stated above). integrated with gas leak detection and isolation system alongside the appropriate Safety Integrity Level (SIL) rated devices.

- **Controlled Venting:** CO_2 venting from pre/post-compression systems to be controlled to avoid low temperature conditions within the CC process.
- **Leak points minimisation:** flanging and other potential leak points to be minimised.
- **Plant maintenance management:** appropriate work procedures for the maintenance of CO_2 inventory systems e.g. appropriate isolation systems in place before maintenance activities.

6. **Clarify the statement: 'The outlet of the absorber tower includes a water wash step to scrub emissions of amine and degradation products within the treated flue gas will remove entrained mist droplets and solvent vapour prior to release to atmosphere'. How will the mist droplets and solvent vapour be removed?**

The absorber tower will be designed and equipped with a mist eliminator/demister system to mitigate against the formation of mists and release of solvent vapour through a combination of Collision & Adherence; Coalescence; and Drainage.

- Collision & Adherence: droplets within the eliminator collide with a surface and stick to it.
- Coalescence: these adhered droplets merge together to form larger droplets.
- Drainage: the heavier, larger droplets are then drained away from the vapor stream.

The mist eliminator/demister system will be designed to abate droplets above a specific size threshold. The efficiency of the system will depend on both the distribution of droplet sizes and the design of the eliminator/demister system, which might include mesh pads, vane packs, or other configurations to optimise removal.

Therefore, incorporating the mist eliminator/demister system within the design of the absorber tower will minimise emissions of mist droplets and solvent vapour released with the treated flue gas in accordance with the Environment Agency guidance titled, '*Post-combustion carbon dioxide capture: emerging techniques*'.

7. **Provide a description of how the Leak Detection and Repair (LDAR) system addresses leaks from solvent storage and changes to the hazardous properties of the solvent for different stages in the solvent utility cycle, including fresh, used and waste solvent.**

This information is important in assessing the suitability of LDAR arrangements for the solvent at different stages in the utility cycle.

The Leak Detection and Repair (LDAR) system plays a crucial role in managing solvent storage and meeting environmental standards. The LDAR system is subject to detailed design, the requirements of the system can be summarised as follows:

- **Detection:** LDAR programs uses various methods to detect leaks, such as visual inspections and specialized sensors to catch leaks early, preventing damage and saving resources.
- **Repair:** When leaks are detected, quick action is taken to fix faulty components like valves and pumps, preventing the release of harmful compounds.
- **Monitoring of Hazardous Properties:**

  - Fresh Solvent: Monitoring for changes in pressure or composition to catch leaks early.
  - Used Solvent: Tracking changes in properties as solvents are used, ensuring prompt detection of leaks. Waste Solvent: Detecting a wide range of emissions from waste solvents for effective management.
- **Continuous Improvement:** LDAR programs evolve with technology and regulations, updating methods and tools for better leak detection and repair.

By systematically addressing leaks, the LDAR system will reduce emissions, promoting safety, environmental protection, and regulatory compliance. Furthermore, understanding how solvent properties change throughout their lifecycle improves risk management and environmental performance.

The O&M manuals for the process equipment associated with the use, storage and handling of the solvents will include requirements for the maintenance of the leak detection systems.

4 Solvent selection

8. Confirm how you have worked out the performance of your selected solvent, monoethanolamine (MEA) including how the estimated annual consumption of MEA has been calculated. Reference any pilots or test results you may have used from similar plant.

The CC facility is subject to detailed design; therefore, until this has been completed the consumption of monoethanolamine (MEA) can only be estimated using the design principles which have been applied to the process. The consumption of MEA will be confirmed following the completion of the Front End Engineering Design (FEED) stage.

The estimated annual consumption of MEA was determined using the Aspen HYSYS (v14) modelling software and validated using empirical data, as follows:

- **Process Simulation**: Through Aspen HYSYS, carbon capture process was modelled taking into considering the specific parameters of the CC facility, such as inlet flue gas composition, flow rates, and temperature and pressure conditions.
- **Solvent Performance Evaluation:** The performance of MEA within the simulation was assessed, taking into consideration the absorption efficiency and desorption requirements of the process.
- **Data Calibration:** The results of the simulation were cross referenced with empirical data from pilot studies and similar plant operations to validate the model and ensure its accuracy in representing real-world conditions[1].
- **Annual Consumption Calculation:** The annual consumption of MEA was calculated using the outputs from the validated simulation model to determine solvent usage allowing for the availability of the CC facility, assumed to be 95%.

Following review of the information submitted within the EP application, Viridor Runcorn CCS Limited notes that the estimated consumption provided does not allow for degradation of the solvent due to variability of the CO_2 content of the flue gas or for potential contaminants within the flue gas. Viridor Runcorn CCS Limited has reviewed the assumptions to determine the annual consumption of amine solvent based on reference data[2]. Taking into consideration solvent degradation the annual consumption of amine solvent has been amended, refer to Table 3:

Table 3: Key parameters utilised to determine the annual consumption of MEA

Parameter	Unit	Factor
Key performance parameters of the CC facility		
MEA make-up rate	(kg/h)	43.2
Key consumption data of the CC facility		
MEA Specific Consumption	(kg/tonne CO_2)	0.3
MEA Annual Consumption	(tonne/annum)	360

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[1] "Results from 30% MEA performance testing at the CO_2 Technology Centre Mongstad", Energy Procedia, 13th International Conference on Greenhouse Gas Control Technologies, GHGHT-13, 14-18 November 2016, Lausanne, Switzerland

[2] Moser P. et al., 2011 "Investigation of trace elements in the inlet and outlet streams of a MEA-based post-combustion capture process – Results from the test programme at the Niederaussem pilot plant". Energy Procedia 4, 473-479.

Therefore, allowing for solvent degradation of MEA, the estimated annual consumption of MEA is estimated to be approximately 360 tonnes per annum.

9. **Provide the following information regarding the amine solvent at different stages in the solvent utility cycle:**
   a. **Safety Data Sheet for the MEA solvent.**
   b. **An assessment of any changes to the hazardous properties of the MEA solvent with use including evidence (from pilot plant studies or others) to support this assessment.**
   c. **Waste code(s) for waste solvent generated from the carbon capture facility including waste from the solvent regeneration process, the acid scrubbing process, and the CO2 compression process.**

   We need this information to understand any changes to the hazardous properties of the solvent at different stages in the utility cycle.

An MSDS for MEA is provided in Appendix B.

On behalf of Viridor Runcorn CCS Ltd, Fichtner has undertaken a review of the hazardous properties of the MEA solvent at different stages in the solvent utility cycle, refer to Appendix C.

Viridor Runcorn CCS Ltd assumed that the waste solvent generated by the CC facility will be transferred off-site to a suitably permitted facility utilising the following LoW code:

19 02 05 - sludges from physico/chemical treatment containing substances*

5 Acid wash

10. The process overview supplied in section 3.2 of the Supporting Information document refers to an acid wash. Clarify what acid will be used for the acid wash stage on the carbon capture absorber and update 'Table 1: Types and amounts of primary raw materials' and 'Figure 1: Indicative process schematic for the carbon capture process' in Supporting Information document accordingly.

Following additional design of the CC facility, Viridor Runcorn CCS Ltd can confirm that there will a water wash stage as a final step within the absorber tower, and not an acid wash as presented within the indicative process schematic for the carbon capture process.

Taking this into consideration, the indicative process schematic has been updated to reflect the revised designs, refer to Appendix D. Furthermore, the water wash stage will not require any additional raw materials.

6 Bunding

11. Provide further information regarding the bunding and storage of chemicals including:

a. The size and number of tanks.

b. Type of bund.

In section 4.1 of the document Supporting Information, you have provided some information regarding the storage capacity and bunding and containment. However, further detail is required.

Viridor Runcorn CCS Ltd can confirm that the CC facility will include the following storage tanks:

Table 4: Chemical storage facilities

Material	Estimated storage capacity (tonnes)	Tank/Vessel No.	Diameter x Height
MEA solution (Holding tank)	900	1	12m x 8m
MEA solution (Process storage tank)	60	1	5m x 3m
MEA solution (Process storage tank)	60	1	5m x 3m
Sodium hydroxide (NaOH)	50	1	4m x 2m
Reclaimer solvent sludge	25	1	2.5m x 5m

All storage tanks will be designed in accordance with Environment Agency guidance titled 'Guidance Pollution prevention for businesses', and will be located and designed to ensure that:

- no other materials are stored within the bund;
- accumulated rainwater can be removed regularly, if required; and
- the contents of storage facilities are not able to enter surface water or groundwater; and
- they are located:
  - 10m from watercourses, open drains, gullies, unsurfaced areas or porous surfaces; and
  - 50m from wells, springs or boreholes.

Chemical bunds will have a minimum capacity of 110% of the largest container or 25% of the total stored volume, whichever is greater. Bunds will be impermeable and resistant to the chemicals they contain. They will be maintained regularly to prevent leaks. Bund water collected will be tested prior to its discharge.

7 Wastewater treatment

12. **Provide further details on the proposed wastewater treatment plant. This should include, but is not limited to:**
    a. **Information on how the pollutants from carbon capture facility (Section 6.3 in the Environmental Risk Assessment), including amine solvent and its degradation products, will be disposed of and the environmental fates of the amine solvent/degradation products.**
    b. **Flow diagrams (and explanation) showing:**
        i. **Inputs and outputs for the wastewater treatment plant (Note: there is no reference to the water wash in the process flow and the fate of this potential wastewater stream);**
        ii. **Links to the cooling water systems.**
    c. **Waste code(s) for waste sludge generated by the wastewater treatment plant.**

Process flow diagram submitted with the application shows that potentially amine contaminated wastewater from CO2 compression and dehydration stages is passed to the effluent treatment facility.

The Wastewater Treatment Plant (WWTP) proposed for the facility is designed to treat the water condensate from flue gas Direct Contact Cooler (DCC) for re-use as make-up water for the hybrid cooling system. The indicative process schematic for the carbon capture process submitted within the EP application has been updated to reflect the revised designs, refer to Appendix D. This supersedes the process schematic presented in the Supporting Statement.

As explained in section 3.3 of the Supporting Information, the design of the WWTP is subject to detailed design; however, the preliminary designs of the WWTP are assumed to include the following treatment processes/steps:

- physical treatment step to remove suspended particles;
- chemical treatment steps for pH adjustment, precipitation and coagulation;
- ultra filtration and filtration with activated carbon;
- solid sludge management including dewatering, storage, and disposal; and
- a settling/clarification system.

Process effluents generated by the CC facility (effluents from dehydration, compression, as well as any excess/recycled water wash from absorber system) which could potentially be contaminated with amines, they will be recycled within the process as part of the lean amine system. Therefore, the potentially contaminated effluents will not be released to the aquatic environment from the Facility.

Spent amine solvent will be collected in an Amine waste sump/drum then processed in the reclaimer unit. The regenerated amine will be returned to the absorber for re-use within the CC facility, and the residues (degraded amine solvent) will be transferred for storage in a dedicated bunded storage tank for transfer off-site to a suitably permitted waste treatment facility. At this stage it is assumed that the residues will be transferred for high-temperature incineration, but this is subject to agreement being reached with the permitted waste treatment facility.

The hazardous nature of the residues from the wastewater treatment plant will need to be confirmed following detailed design of the water treatment process. However, depending on the nature of the residues, Viridor Runcorn CCS Ltd has assumed that they will be transferred to a suitably permitted waste management facility, depending on the hazardous nature of the residue, using one of the following LoW codes:

1. Hazardous residues:

   19 08 13 - Sludges containing dangerous substances from other treatment of industrial waste water*

2. Non-hazardous residues:

   19 08 14 - Sludges from other treatment of industrial waste water other than those mentioned in 19 08 13

8 Energy efficiency

13. Provide the outline design of the proposed compression system and an assessment of the potential for re-use of waste heat from the CO2 compression system.

Our guidance on Post-combustion carbon dioxide capture: emerging techniques (available here) advises that you should you consider how any waste heat arising may be used.

Whilst it is subject to detailed design, based on the required CO_2 outlet pressure (40 bar gauge) and the export from the installation of CO_2 in a gas phase, as required by Hynet, it is assumed that a 3-stage compressor with intercooling would be required for the compression systems. The compression system would be a high efficiency system to minimise the generation of waste heat which could be available for re-use within the CC facility.

As the compression system will only require a 3-stage compressor and no CO_2 phase change requirements (i.e. no dense phase), the waste heat available from the compression systems will only be low grade heat. Viridor Runcorn CC Limited will ensure that energy efficiency is a key consideration within the detailed design phase of the CC facility including the CO_2 compression systems.

9 Other than normal operating conditions (OTNOC)

14. **Please confirm that you will produce an OTNOC management plan that meets the requirements of our revised guidance on emerging techniques.**

    Our revised guidance on emerging techniques (available from this link) states: 'You should set out any potential 'other than normal operating conditions (OTNOC)' for the CO2 capture plant in your permit application and include a PCC OTNOC management plan in your management system to measure and minimise occurrence and impact of these periods.

    Your PCC OTNOC management plan must compliment any OTNOC management plan for the facility it serves and consider internal and external causes of OTNOC.

Viridor Runcorn CCS Limited can confirm that it will produce an OTNOC Management Plan for the CC facility, that satisfies the latest requirements on emerging techniques.

10 Other plans and drawings

15. Provide site infrastructure plans which show the locations of, but are not limited to, storage of hazardous materials, buildings, entrances and exits, drainage flows and discharge points.

We understand that you might not have the final design, but indicative plans and drawings should be provided. Further information on requirements of site infrastructure plans can be found here.

Site plans identifying the following information are provided in Appendix D:

- hazardous materials storage;
- site access and egress points;
- indicative drainage flows; and
- emission points – this was provided within the original application pack.

It should be noted that all buildings associated with the CC facility are identified on the installation and emission point drawings provided in the original application.

Appendices

A Responsibilities Matrix

FICHTNER
Consulting Engineers Limited

Viridor Energy Limited and Viridor CC Runcorn Limited

Runcorn ERF

Interface Responsibilities

This document has been developed to identify the responsibilities associated with the interfaces between the Runcorn ERF (Viridor Energy Limited) and the associated Carbon Capture facility (CC facility) (Viridor CC Ltd).

Interface	**Activity**	**Viridor ERF EP Responsibilities**	**Viridor CC EP Responsibilities**
Provision of heat and power	Viridor ERF will provide Viridor CC with heat and power for the operation of the CC facility.	Viridor ERF will only export heat and power to the CC facility when it is in a ‘steady state’. Maintenance of the utilities and supply systems. Reporting of Viridor CC energy supply/consumption to the EA as part of the performance parameters for the ERF.	Reporting of Viridor CC energy consumption data to the EA SEPA as part of the reporting of performance parameters. In the event of a loss of heat and power from the ERF, the CC facility will enter an emergency shutdown sequence.
Provision of steam	Operation of the back-pressure turbine	Viridor ERF will supply steam to the CC facility which will be used in the back-pressure turbine.	Viridor CC will operate the back-pressure turbine. All power generated by the back-pressure turbine will be consumed within the CC facility.
Flue gases from the ERF transferred for treatment in the CC facility	Start-up of the CC facility	Viridor ERF will not transfer flue gases from the ERF to the CC facility unless the ERF is in steady state. Prior to opening the damper on the flue gas duct to enable the transfer of flue gases from the ERF to the cc facility, Viridor ERF will	Prior to the transfer of flue gases, Viridor CC will confirm to Viridor ERF that it is ‘available’ to receive the flue gases.

Interface	Activity	Viridor ERF EP Responsibilities	Viridor CC EP Responsibilities
		confirm with Viridor CC facility that it is 'available' to receive the flue gases. In the event that the CC facility is not available, Viridor ERF will not open the damper.	
Flue gases from the ERF transferred for treatment in the CC facility	Normal operation of the ERF	Viridor ERF will open the damper to allow for the transfer of flue gases from the ERF to the duct which connects to the CC facility.	Viridor CC will operate the CC facility to enable the capture of CO_2 from the flue gases.
Flue gases from the ERF transferred for treatment in the CC facility	Abnormal operation of the ERF	Viridor ERF will close the damper to inhibit the transfer of flue gases from the ERF to CC facility during abnormal operation.	Viridor CC will shutdown the CC facility until requested to restart the process by Viridor ERF.
Flue gases from the ERF transferred for treatment in the CC facility	Emergency shutdown of the CC facility	Viridor ERF will monitor emissions from the ERF for compliance with the emission limits within the EP using the CEMS in the main stack.	In the event of an emergency shutdown, the CC facility will have capability to close the flue gas damper to inhibit the transfer from the ERF.
Flue gases from the ERF transferred for treatment in the CC facility	Emergency shutdown of the ERF	Viridor ERF will close the damper to inhibit the transfer of flue gases from the ERF to CC facility during abnormal operation.	Viridor CC will shutdown the CC facility until requested to restart the process by Viridor ERF.
Access for monitoring	Periodic emissions monitoring	Viridor ERF will contact Viridor CC in advance of arranging for the monitoring of emissions from the ERF. Prior to the relevant representatives attending the Site to undertake the monitoring, Viridor ERF will confirm the arrangements for	Viridor CC will make arrangements for the relevant representatives (employees or contractors) to gain access to the monitoring platforms/equipment within the CC facility to undertake periodic monitoring of emissions from the ERF.

Interface	Activity	Viridor ERF EP Responsibilities	Viridor CC EP Responsibilities
		monitoring with Viridor CC.	
Access for monitoring	Maintenance of monitoring systems	Viridor ERF will contact Viridor CC to advise that it is proposed to undertake maintenance on the monitoring systems for the ERF. Prior to the relevant representatives attending the Site to undertake the maintenance, Viridor ERF will confirm the arrangements for undertaking the maintenance with Viridor CC.	Viridor CC will make arrangements for the relevant representatives (employees or contractors) to gain access to the monitoring platforms/equipment within the CC facility to undertake maintenance on the monitoring systems for the ERF.
Emergency response procedures	Mutual training/induction	Train Viridor CC staff in the installation’s emergency response procedures.	Training Viridor ERF operators in the emergency response procedures specific to the CC facility.
Site Access	Waste delivery, raw material delivery and residue removal vehicles share common access roads to the Site. Viridor ERF and Viridor CC workers share common access roads.	Maintenance of access routes to and from the CC facility in a state suitable for waste delivery, raw material delivery and residue removal vehicles.	Viridor CC employees to comply with the installation-wide requirements for vehicle movements.
Weighbridge	Waste vehicles share the installation weighbridge.	Weighbridge provision provided that the vehicles associated with the CC facility do not cause any significant delays to Viridor ERF’s waste vehicle movements. Maintenance of the weighbridge. Ensuring the weighbridge is available at all times.	Where practicable, scheduling of vehicle movements outside of peak waste delivery hours to avoid causing delays to waste vehicles accessing the installation.

Interface	Activity	Viridor ERF EP Responsibilities	Viridor CC EP Responsibilities
External telephone communications	24-hour contact to the ERF and CC facility.	Viridor ERF will provide a 24-hour contact to the installation to enable complaints to be reported. Where appropriate, Viridor CC will undertake an investigation to determine whether the complaint was due to the operation of the CC facility.	When instructed by Viridor ERF of a complaint, Viridor CC will undertake an investigation to determine whether the complaint was due to the operation of the CC facility.

B MSDS – MEA

SAFETY DATA SHEET

Version 6.7
Revision Date 03/18/2023
Print Date 04/01/2023

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifiers

Product name : Ethanolamine

Product Number : 398136
Brand : Sigma-Aldrich
Index-No. : 603-030-00-8
CAS-No. : 141-43-5

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses : Laboratory chemicals, Synthesis of substances

1.3 Details of the supplier of the safety data sheet

Company : Sigma-Aldrich Inc.
3050 SPRUCE ST
ST. LOUIS MO 63103
UNITED STATES

Telephone : +1 314 771-5765
Fax : +1 800 325-5052

1.4 Emergency telephone

Emergency Phone # : 800-424-9300 CHEMTREC (USA) +1-703-527-3887 CHEMTREC (International) 24 Hours/day; 7 Days/week

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

GHS Classification in accordance with 29 CFR 1910 (OSHA HCS)

Flammable liquids (Category 4), H227
Acute toxicity, Oral (Category 4), H302
Acute toxicity, Inhalation (Category 4), H332
Acute toxicity, Dermal (Category 4), H312
Skin corrosion (Category 1B), H314
Serious eye damage (Category 1), H318
Specific target organ toxicity - single exposure (Category 3), Respiratory system, H335
Short-term (acute) aquatic hazard (Category 2), H401
Long-term (chronic) aquatic hazard (Category 3), H412

For the full text of the H-Statements mentioned in this Section, see Section 16.

2.2 GHS Label elements, including precautionary statements

Pictogram

Signal Word Danger

Hazard statement(s)

H227	Combustible liquid.
H302 + H312 + H332	Harmful if swallowed, in contact with skin or if inhaled.
H314	Causes severe skin burns and eye damage.
H335	May cause respiratory irritation.
H401	Toxic to aquatic life.
H412	Harmful to aquatic life with long lasting effects.

Precautionary statement(s)

P210	Keep away from heat/ sparks/ open flames/ hot surfaces. No smoking.
P261	Avoid breathing mist or vapors.
P264	Wash skin thoroughly after handling.
P270	Do not eat, drink or smoke when using this product.
P271	Use only outdoors or in a well-ventilated area.
P273	Avoid release to the environment.
P280	Wear protective gloves/ protective clothing/ eye protection/ face protection.
P301 + P312 + P330	IF SWALLOWED: Call a POISON CENTER/ doctor if you feel unwell. Rinse mouth.
P301 + P330 + P331	IF SWALLOWED: Rinse mouth. Do NOT induce vomiting.
P303 + P361 + P353	IF ON SKIN (or hair): Take off immediately all contaminated clothing. Rinse skin with water/ shower.
P304 + P340 + P310	IF INHALED: Remove person to fresh air and keep comfortable for breathing. Immediately call a POISON CENTER/ doctor.
P305 + P351 + P338 + P310	IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Immediately call a POISON CENTER/ doctor.
P363	Wash contaminated clothing before reuse.
P370 + P378	In case of fire: Use dry sand, dry chemical or alcohol-resistant foam to extinguish.
P403 + P233	Store in a well-ventilated place. Keep container tightly closed.
P403 + P235	Store in a well-ventilated place. Keep cool.
P405	Store locked up.
P501	Dispose of contents/ container to an approved waste disposal plant.

2.3 Hazards not otherwise classified (HNOC) or not covered by GHS - none

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SECTION 3: Composition/information on ingredients

3.1 Substances

Synonyms : Monoethanolamine
2-Aminoethyl alcohol
2-Aminoethanol

Formula : C_2H_7NO
Molecular weight : 61.08 g/mol
CAS-No. : 141-43-5

EC-No. : 205-483-3
Index-No. : 603-030-00-8

Component	Classification	Concentration
ethanolamine		
	Flam. Liq. 4; Acute Tox. 4; Skin Corr. 1B; Eye Dam. 1; STOT SE 3; Aquatic Acute 2; Aquatic Chronic 3; H227, H302, H332, H312, H314, H318, H335, H401, H412 Concentration limits: >= 5 %: STOT SE 3, H335;	<= 100 %

For the full text of the H-Statements mentioned in this Section, see Section 16.

SECTION 4: First aid measures

4.1 Description of first-aid measures

General advice
First aiders need to protect themselves. Show this material safety data sheet to the doctor in attendance.

If inhaled
After inhalation: fresh air. Immediately call in physician. If breathing stops: immediately apply artificial respiration, if necessary also oxygen.

In case of skin contact
In case of skin contact: Take off immediately all contaminated clothing. Rinse skin with water/ shower. Call a physician immediately.

In case of eye contact
After eye contact: rinse out with plenty of water. Immediately call in ophthalmologist. Remove contact lenses.

If swallowed
After swallowing: make victim drink water (two glasses at most), avoid vomiting (risk of perforation). Call a physician immediately. Do not attempt to neutralise.

4.2 Most important symptoms and effects, both acute and delayed

The most important known symptoms and effects are described in the labelling (see section 2.2) and/or in section 11

4.3 Indication of any immediate medical attention and special treatment needed

No data available

SECTION 5: Firefighting measures

5.1 Extinguishing media

Suitable extinguishing media
Water Foam Carbon dioxide (CO2) Dry powder

Unsuitable extinguishing media
For this substance/mixture no limitations of extinguishing agents are given.

5.2 Special hazards arising from the substance or mixture

Carbon oxides
Nitrogen oxides (NOx)
Combustible.
Vapors are heavier than air and may spread along floors.
Forms explosive mixtures with air on intense heating.
Development of hazardous combustion gases or vapours possible in the event of fire.

5.3 Advice for firefighters

Stay in danger area only with self-contained breathing apparatus. Prevent skin contact by keeping a safe distance or by wearing suitable protective clothing.

5.4 Further information

Remove container from danger zone and cool with water. Suppress (knock down) gases/vapors/mists with a water spray jet. Prevent fire extinguishing water from contaminating surface water or the ground water system.

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures

Advice for non-emergency personnel: Do not breathe vapors, aerosols. Avoid substance contact. Ensure adequate ventilation. Keep away from heat and sources of ignition. Evacuate the danger area, observe emergency procedures, consult an expert.
For personal protection see section 8.

6.2 Environmental precautions

Do not let product enter drains.

6.3 Methods and materials for containment and cleaning up

Cover drains. Collect, bind, and pump off spills. Observe possible material restrictions (see sections 7 and 10). Take up with liquid-absorbent and neutralising material (e.g. Chemizorb® OH^-, Merck Art. No. 101596). Dispose of properly. Clean up affected area.

6.4 Reference to other sections

For disposal see section 13.

SECTION 7: Handling and storage

7.1 Precautions for safe handling

Advice on safe handling
Work under hood. Do not inhale substance/mixture. Avoid generation of vapours/aerosols.

Advice on protection against fire and explosion
Keep away from open flames, hot surfaces and sources of ignition.Take precautionary measures against static discharge.

Hygiene measures
Immediately change contaminated clothing. Apply preventive skin protection. Wash hands and face after working with substance.
For precautions see section 2.2.

7.2 Conditions for safe storage, including any incompatibilities

Storage conditions
Tightly closed.

hygroscopic Handle and store under inert gas.

Storage class
Storage class (TRGS 510): 8A: Combustible, corrosive hazardous materials

7.3 Specific end use(s)

Apart from the uses mentioned in section 1.2 no other specific uses are stipulated

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SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Ingredients with workplace control parameters

Component	CAS-No.	Value	Control parameters	Basis
ethanolamine	141-43-5	TWA	3 ppm	USA. ACGIH Threshold Limit Values (TLV)
		STEL	6 ppm	USA. ACGIH Threshold Limit Values (TLV)
		TWA	3 ppm 6 mg/m3	USA. Occupational Exposure Limits (OSHA) - Table Z-1 Limits for Air Contaminants
		TWA	3 ppm 8 mg/m3	USA. NIOSH Recommended Exposure Limits
		ST	6 ppm 15 mg/m3	USA. NIOSH Recommended Exposure Limits
		PEL	3 ppm 8 mg/m3	California permissible exposure limits for chemical contaminants (Title 8, Article 107)
		STEL	6 ppm 15 mg/m3	California permissible exposure limits for chemical contaminants (Title 8, Article 107)

8.2 Exposure controls

Appropriate engineering controls
Immediately change contaminated clothing. Apply preventive skin protection. Wash hands and face after working with substance.

Personal protective equipment

Eye/face protection
Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU). Tightly fitting safety goggles

Skin protection
This recommendation applies only to the product stated in the safety data sheet, supplied by us and for the designated use. When dissolving in or mixing with other substances and under conditions deviating from those stated in EN374 please

contact the supplier of CE-approved gloves (e.g. KCL GmbH, D-36124 Eichenzell, Internet: www.kcl.de).
Full contact
Material: Latex gloves
Minimum layer thickness: 0.6 mm
Break through time: 480 min
Material tested:Lapren® (KCL 706 / Aldrich Z677558, Size M)

This recommendation applies only to the product stated in the safety data sheet, supplied by us and for the designated use. When dissolving in or mixing with other substances and under conditions deviating from those stated in EN374 please contact the supplier of CE-approved gloves (e.g. KCL GmbH, D-36124 Eichenzell, Internet: www.kcl.de).
Splash contact
Material: Nitrile rubber
Minimum layer thickness: 0.11 mm
Break through time: 10 min
Material tested:KCL 741 Dermatril® L

Body Protection
protective clothing

Respiratory protection
required when vapours/aerosols are generated. Our recommendations on filtering respiratory protection are based on the following standards: DIN EN 143, DIN 14387 and other accompanying standards relating to the used respiratory protection system.

Control of environmental exposure
Do not let product enter drains.

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

a)	Appearance	Form: liquid, clear Color: colorless
b)	Odor	amine-like
c)	Odor Threshold	No data available
d)	pH	12.1 at 100 g/l at 20 °C (68 °F)
e)	Melting point/freezing point	Melting point/range: 10 - 11 °C (50 - 52 °F) - lit.
f)	Initial boiling point and boiling range	170 °C 338 °F - lit. 69 - 70 °C (156 - 158 °F) at 13 hPa
g)	Flash point	91 °C (196 °F) at ca.1,013 hPa - Pensky-Martens closed cup - ISO 2719
h)	Evaporation rate	No data available
i)	Flammability (solid, gas)	No data available
j)	Upper/lower flammability or explosive limits	Upper explosion limit: 17 %(V) Lower explosion limit: 2.5 %(V)

k)	Vapor pressure	0.5 hPa at 20 °C (68 °F) - (calculated)
l)	Vapor density	2.11 - (Air = 1.0)
m)	Density	1.012 g/cm3 at 25 °C (77 °F) - lit.
	Relative density	No data available
n)	Water solubility	1,000 g/l at 20 °C (68 °F) - completely miscible
o)	Partition coefficient: n-octanol/water	log Pow: -2.3 at 25 °C (77 °F) - Bioaccumulation is not expected.
p)	Autoignition temperature	424 °C (795 °F) at 1,013 hPa - ASTM E-659
q)	Decomposition temperature	No data available
r)	Viscosity	23.5 mm2/s at 20 °C (68 °F) - 9.8 mm2/s at 40 °C (104 °F) -
s)	Explosive properties	No data available
t)	Oxidizing properties	none

9.2 Other safety information

Relative vapor density	2.11 - (Air = 1.0)

SECTION 10: Stability and reactivity

10.1 Reactivity

Forms explosive mixtures with air on intense heating.
A range from approx. 15 Kelvin below the flash point is to be rated as critical.

10.2 Chemical stability

The product is chemically stable under standard ambient conditions (room temperature) .
Absorbs carbon dioxide (CO2) from air.

10.3 Possibility of hazardous reactions

No data available

10.4 Conditions to avoid

Exposure to moisture.
Strong heating.

10.5 Incompatible materials

No data available

10.6 Hazardous decomposition products

In the event of fire: see section 5

SECTION 11: Toxicological information

11.1 Information on toxicological effects

Acute toxicity
LD50 Oral - Rat - male and female - 1,089 mg/kg
(OECD Test Guideline 401)
Acute toxicity estimate Inhalation - 11.1 mg/l - vapor

(Expert judgment)
LD50 Dermal - Rabbit - 1,015 mg/kg
Remarks: (RTECS)

Skin corrosion/irritation
Skin - Rabbit
Result: Corrosive - 4 h
(OECD Test Guideline 404)

Serious eye damage/eye irritation
Eyes - Rabbit
Result: Corrosive
(OECD Test Guideline 405)
Remarks: Causes serious eye damage.

Respiratory or skin sensitization
Maximization Test - Guinea pig
Result: negative
Remarks: (ECHA)

Germ cell mutagenicity
Test Type: Ames test
Test system: Escherichia coli/Salmonella typhimurium
Metabolic activation: with and without metabolic activation
Method: OECD Test Guideline 471
Result: negative
Test Type: Chromosome aberration test in vitro
Test system: rat hepatocytes
Metabolic activation: without metabolic activation
Method: OECD Test Guideline 473
Result: negative
Test Type: In vitro mammalian cell gene mutation test
Test system: mouse lymphoma cells
Metabolic activation: with and without metabolic activation
Method: OECD Test Guideline 476
Result: negative
Test Type: In vitro mammalian cell gene mutation test
Test system: Chinese hamster fibroblasts
Metabolic activation: without metabolic activation
Result: negative
Remarks: (ECHA)

Test Type: In vivo micronucleus test
Species: Mouse
Cell type: Bone marrow
Application Route: Oral
Method: OECD Test Guideline 474
Result: negative

Carcinogenicity

IARC:	No ingredient of this product present at levels greater than or equal to 0.1% is identified as probable, possible or confirmed human carcinogen by IARC.
NTP:	No ingredient of this product present at levels greater than or equal to 0.1% is identified as a known or anticipated carcinogen by NTP.
OSHA:	No component of this product present at levels greater than or equal to 0.1% is on OSHA’s list of regulated carcinogens.

Reproductive toxicity
No data available

Specific target organ toxicity - single exposure
May cause respiratory irritation.

Specific target organ toxicity - repeated exposure
No data available

Aspiration hazard
No data available

11.2 Additional Information

Repeated dose toxicity - Rat - male and female - Oral - > 75 Days - NOAEL (No observed adverse effect level) - 300 mg/kg
Remarks: (ECHA)

RTECS: KJ5775000
Liver - Irregularities - Based on Human Evidence

Liver - Irregularities - Based on Human Evidence

SECTION 12: Ecological information

12.1 Toxicity

Toxicity to fish	semi-static test LC50 - Cyprinus carpio (Carp) - 349 mg/l - 96 h (Tested according to Directive 92/69/EEC.)
Toxicity to daphnia and other aquatic invertebrates	static test EC50 - Daphnia magna (Water flea) - 65 mg/l - 48 h (Regulation (EC) No. 440/2008, Annex, C.2)
Toxicity to algae	static test ErC50 - Pseudokirchneriella subcapitata (green algae) - 2.8 mg/l - 72 h (OECD Test Guideline 201)
	static test NOEC - Pseudokirchneriella subcapitata (green algae) - 1 mg/l - 72 h (OECD Test Guideline 201)
Toxicity to bacteria	static test EC10 - activated sludge - > 1,000 mg/l - 30 min (OECD Test Guideline 209)
Toxicity to fish(Chronic toxicity)	flow-through test NOEC - Oryzias latipes - 1.24 mg/l - 41 d (OECD Test Guideline 210)
Toxicity to daphnia	semi-static test NOEC - Daphnia magna (Water flea) - 0.85 mg/l -

and other aquatic invertebrates(Chronic toxicity)	21 d (OECD Test Guideline 202)

12.2 Persistence and degradability

Biodegradability	aerobic - Exposure time 21 d Result: > 90 % - Readily biodegradable. (OECD Test Guideline 301A) Result: 90 - 100 % - Readily biodegradable. (OECD Test Guideline 301F)
Biochemical Oxygen Demand (BOD)	800 mg/g Remarks: (IUCLID)
Theoretical oxygen demand	1,310 mg/g Remarks: (IUCLID)

12.3 Bioaccumulative potential

No data available

12.4 Mobility in soil

No data available

12.5 Results of PBT and vPvB assessment

PBT/vPvB assessment not available as chemical safety assessment not required/not conducted

12.6 Endocrine disrupting properties

No data available

12.7 Other adverse effects

Additional ecological information	Toxic to aquatic life. An environmental hazard cannot be excluded in the event of unprofessional handling or disposal.

SECTION 13: Disposal considerations

13.1 Waste treatment methods

Product

Waste material must be disposed of in accordance with the national and local regulations. Leave chemicals in original containers. No mixing with other waste. Handle uncleaned containers like the product itself. See www.retrologistik.com for processes regarding the return of chemicals and containers, or contact us there if you have further questions.

SECTION 14: Transport information

DOT (US)

UN number: 2491 Class: 8 Packing group: III
Proper shipping name: Ethanolamine
Reportable Quantity (RQ):
Poison Inhalation Hazard: No

IMDG

UN number: 2491 Class: 8 Packing group: III EMS-No: F-A, S-B
Proper shipping name: ETHANOLAMINE

IATA
UN number: 2491 Class: 8 Packing group: III
Proper shipping name: Ethanolamine

SECTION 15: Regulatory information

SARA 302 Components
This material does not contain any components with a section 302 EHS TPQ.

SARA 313 Components
This material does not contain any chemical components with known CAS numbers that exceed the threshold (De Minimis) reporting levels established by SARA Title III, Section 313.

SARA 311/312 Hazards
Fire Hazard, Acute Health Hazard, Chronic Health Hazard

Massachusetts Right To Know Components

	CAS-No.	Revision Date
ethanolamine	141-43-5	2007-03-01

Pennsylvania Right To Know Components

	CAS-No.	Revision Date
ethanolamine	141-43-5	2007-03-01

SECTION 16: Other information

Further information
The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Sigma-Aldrich Corporation and its Affiliates shall not be held liable for any damage resulting from handling or from contact with the above product. See www.sigma-aldrich.com and/or the reverse side of invoice or packing slip for additional terms and conditions of sale.

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C Hazardous Properties of MEA

C.1 Introduction

The hazards associated with MEA are described in the Material Safety Data Sheet (MSDS) provided in Appendix B. The hazards are summarised in Table 5.

Table 5: Hazards classification

Hazard	Hazard Statement
Flammable liquids (category 4)	H227: Combustible liquid
Acute toxicity, oral (category 4)	H302: Harmful if swallowed
Acute toxicity, Inhalation (category 4)	H332: Harmful if inhaled
Acute toxicity, dermal (category 4)	H312: Harmful if in contact with skin
Skin corrosion (category 1b)	H314: Causes severe skin burns and eye damage
Serious eye damage (category 1)	H318: Causes serious eye damage
Specific target organ toxicity (category 3)	H335: May cause respiratory irritation
Short-term (chronic) aquatic hazard (category 2)	H401: Toxic to aquatic life
Long-term (chronic) aquatic hazard (category 3)	H412: Harmful to aquatic life with long lasting effects

Source: Sigma Aldrich

The purpose of this assessment is to determine whether the hazardous properties of MEA change with use in the carbon capture process.

C.2 Carbon capture process overview

The ERF consists of four lines and a single CC facility is used to treat the gaseous emissions produced by the ERF. CO_2 is extracted using an MEA solvent from the mixture of gases from the ERF to create a CO_2 rich stream. Concentrated MEA is delivered to site in appropriate tankers and diluted with water on site to provide a 30% solution of MEA.

A direct contact cooler (DCC) is used to cool/quench the flue gases. In addition, the DCC includes a caustic scrubber to remove acid gases. Following the flue gas quenching and scrubbing the flue gas is ducted to a packed bed absorption column where the CO_2 is scrubbed out through contact with the MEA solvent in a counter current flow regime. A chemical reaction occurs between the CO_2 in the solvent and the MEA, which enables the CO_2 to be captured in the solvent. The CO_2 loaded solvent is referred to as the rich MEA.

When CO_2 is absorbed into MEA, an intermediate known as MEA carbamate, or MEACOO-, is formed. Typically, up to 0.5 moles of CO_2 can be absorbed into MEA (as carbamate) per mole of MEA.

The treated flue gases leave the absorber via a water wash to scrub emissions of amine and degradation products within the treated flue gases. The absorption of CO_2 within the absorber column will release heat which will increase the temperature of the treated flue gases.

The CO_2 rich amine solution is drained from the absorber sump and pumped to the stripper to extract the captured CO_2 from the CO_2 rich amine solution and regenerate the amine solution. Heat from the reboiler will raise the temperature of the CO_2 rich amine solution to release the captured CO_2 and produce a hot lean-amine solution which can be recirculated back to the absorber tower.

The CO_2 from the stripper will be saturated with water and traces of oxygen will be present and must be treated prior to release to the CO_2 transport network. Prior to the captured CO_2 being compressed it must be conditioned, through dehydration and deoxygenation to produce a CO_2 product which satisfies Hynet's pipeline transport and export requirements.

The operating temperatures and composition of MEA in key parts of the process are summarised in Table 6.

Table 6: Operating temperatures for the CCS facility

Key process units and streams	Function	Temperature (°C)	Composition of MEA
Lean transfer line to absorber	-	37-60	MEA
Absorber	Absorption of CO_2 into lean MEA	43-60	Liquid inlet: MEA Liquid outlet: MEA + CO_2 (MEACOO-)
Rich transfer line to rich-lean heat exchanger	-	42	MEA + CO_2 (MEACOO-)
Rich-lean heat exchanger	Heat exchange from the hot lean MEA from the stripper to the cool rich solvent from the absorber	Rich side: 42 Lean side: 110	Rich side: MEA + CO_2 (MEACOO-) Lean side: MEA
Rich transfer line to stripper inlet	-	110	MEA + CO_2 (MEACOO-)
Stripper	Desorption of CO_2 from rich MEA	110-125	Liquid inlet: MEA + CO_2 (MEACOO-) Liquid outlet: MEA
Lean transfer line to rich-lean heat exchanger	-	125	MEA

Source: Aspentech

C.3 Factors that affect the hazardous properties of MEA

As MEA is used its properties change as a result of:

1. the concentration;
2. the process operating temperatures;
3. reaction with CO_2; and
4. degradation of the solvent.

C.3.1 Concentration of MEA

The delivered MEA is diluted with water to generate the 30% MEA solution required for the process. Water is not a hazardous substance. Therefore, due to dilution the MEA becomes less hazardous with respect to all hazards described in Table 5.

C.3.2 Process operating conditions

Hot MEA, at a temperature above 100°C, is known to be more corrosive than cooler MEA (Kittel et al. 2009; Hjelmaas et al., 2016). The flash point of MEA is 86°C – 94°C. Therefore, MEA becomes more flammable when the temperature exceeds 86°C. Furthermore, high temperatures will have a negative impact on the MEA (section C.3.4).

C.3.3 Reaction with CO_2

MEA carbamate is produced as an intermediate when CO_2 is absorbed into MEA. Amine carbamates are known to be corrosive (Sedransk Campbell et al., 2016). The MEA carbamate gives up the CO_2 in the stripper and reboiler where the lean solvent is regenerated.

C.3.4 Degradation of the solvent

MEA interacts with O_2, NO_x, SO_3 and any residual heavy metals in the flue gas. Therefore, degradation of MEA will occur over many capture cycles. Degradation can also occur due to high temperatures in the stripper and reboiler.

Oxidative degradation is the dominant mechanism by which the amine degrades (Lepaumier et al., 2011). This occurs mainly in the absorber where the MEA can react with oxygen in the flue gas. Some oxidative degradation reactions are thought to be catalysed by heavy metals (Voice et al., 2013). This could mean the presence of residual heavy metals in the flue gas or in the solvent from corrosion which increases degradation. The dominant product of oxidative degradation is thought to be ammonia.

C.3.5 Summary of factors which might affect the hazardous properties of MEA

MEA at higher concentration (prior to dilution) is more hazardous with respect to all hazards of MEA.

Increasing operating temperature and absorption of CO_2 into MEA are both known to increase the corrosivity of the MEA solvent. When operating temperature increases above 86°C (the flash point) MEA becomes more flammable.

The operating temperature and reaction of CO_2 into the solvent are not known to alter or introduce any other hazardous properties of MEA.

Degradation of the solvent introduces new compounds to the solvent. The presence of these degradation products could introduce additional hazardous properties to those described in Table 5.

C.4 Assessment of hazardous properties and mitigation factors

Pilot campaigns using 30% MEA have been reviewed (where relevant) to provide further detail about the hazardous properties of MEA that may change with use. This includes assessment of where in the process the hazardous properties change and the suitability of measures for mitigating the hazardous properties.

As identified in the previous section, the hazardous properties that change with use of MEA are corrosivity, flammability, and properties arising from the formation of degradation products.

C.4.1 Corrosivity

Increased operating temperatures, increased CO_2 loading, and degradation of the solvent are all thought to contribute to the increasing corrosivity (Hjelmaas et al., 2016; Thompson et al. 2017).

Hjelmaas et al. (2016) and Kittel et al. (2009) analysed rates of corrosion using corrosion coupons of different materials in 30% MEA pilot campaigns. Corrosion coupons are in-line corrosion monitoring devices. Both demonstrated highest rates of corrosion with hot MEA (100°C to 120°C), rich and lean, using carbon steel coupons. MEA at these temperatures is found:

1. at the rich transfer line to stripper inlet from the heat exchanger;
2. in the stripper;
3. in the reboiler, and
4. at the lean transfer line from the stripper inlet to the heat exchanger.

Relatively low rates of corrosion were observed at the absorber inlet and outlet (Kittel et al., 2009; Hjelmaas et al., 2016), where temperatures are cooler.

Stainless steel (SS)304L and SS316L coupons demonstrated excellent general corrosion resistance regardless of temperature or CO_2 loading in both the works of Hjelmaas et al. (2016) and Kittel et al. (2009). However, Hjelmaas et al. (2016) observed some pitting of SS316L coupons when exposed to hot rich MEA. This was not observed by Kittel et al. (2009).

These pilot studies demonstrate that although hot MEA is corrosive, the correct choice of construction materials can mitigate this. All piping in the CC facility that transports the amine solvent will be constructed of corrosion resistant stainless steel. The stripper and the absorber will be constructed of SS304L, with the internals made from SS316L. Although the work by Hjelmaas et al. (2016) demonstrated some pitting with SS316L, it is generally considered to be a highly corrosion resistant material.

Table 7 summarises the relative corrosivity of the MEA solvent at different stages in the utility cycle and the mitigation factors that will be in place at the CC facility.

Table 7: Corrosivity of the MEA solvent at different stages in the utility cycle

Key process units and streams	**Temperature (°C)**	**Loading**	**Relative corrosivity**	**Mitigation factor at CCS facility**
Lean transfer line to absorber	37-60	Lean MEA	Low	SS304L construction; bund
Absorber	43-60	Liquid inlet: Lean MEA Liquid outlet: Rich MEA	Low	SS304L, internals SS316L construction; bund

Key process units and streams	Temperature (°C)	Loading	Relative corrosivity	Mitigation factor at CCS facility
Rich transfer line to rich-lean heat exchanger	42	Rich MEA	Low	SS304L construction; bund
Rich-lean heat exchanger	Rich side: 42 Lean side: 110	Rich side: Rich MEA Lean side: Lean MEA	Medium	SS304L, internals SS316L construction; bund
Rich transfer line to stripper inlet	110	Lean MEA	High	SS304L construction; bund
Stripper	110-125	Liquid inlet: Rich MEA Liquid outlet: Lean MEA	High	SS304L, internals SS316L construction; bund
Lean transfer line to rich-lean heat exchanger	125	Rich MEA	High	SS304L construction; bund

Source: Aspen HYSES model

C.4.2 Flammability

The flash point of MEA is 86°C – 94°C. This means that when the temperature of MEA is above 86°C it becomes more flammable. Flammability is a physical property of MEA which is only dependent on temperature, so there has been no reason for researchers to assess this in CC pilot plant campaigns.

The areas of the process at CC facility where MEA is contained at temperatures above 86°C are the rich-lean heat exchanger, the stripper, the reboiler and the pipes in between these units. During normal operation the flammability of MEA at high temperatures is not a risk as it is contained within the process. However, if MEA with a temperature above 86°C leaked from the process this would be hazardous.

All tanks and pipes would be adequately maintained and inspected regularly. In the event of a leak, a suitable spill kit would be used which would mitigate against the flammability of MEA.

C.4.3 Other hazardous properties

Other hazardous properties may be introduced by solvent degradation products. Degradation occurs gradually over many capture cycles, so these products are not necessarily linked to a particular stage of the utility cycle.

A literature review of solvent degradation compounds observed in 30% MEA pilot campaigns (Morken et al., 2014; Thompson et al., 2017; Morken et al., 2017; Neerup et al., 2023) was undertaken to determine which, if any, degradation products might be present in sufficient quantities to change the hazardous properties of MEA.

The literature revealed that there are two categories of degradation compounds which might have the potential to impact the hazardous properties of the solvent:

- nitrosamines and nitramines; and
- ammonia.

Nitrosamines and nitramines are relevant because they are potentially harmful even in very small quantities. Ammonia is relevant because it was demonstrated to be the dominant degradation product.

C.4.3.1 Nitrosamines and nitramines

Nitrosamines and nitramines are consistently reported to be the main degradation compounds of concern in the literature (SEPA, 2015; Morken et al., 2017; Spietz et al., 2017; Buvik et al., 2021). This is because they are known carcinogens and potentially harmful even in small quantities. Some nitrosamines and nitramines are also known to be acutely toxic to humans and aquatic life. These are both hazards already associated with MEA. Therefore, the main hazardous property introduced by nitrosamines and nitramines is carcinogenicity.

Some of these compounds are volatile and will be emitted to the surrounding environment in the flue gas whilst others will remain in the bulk amine solution.

Generally, stable nitrosamines are formed from reactions between NO_2 in the flue gas and secondary amines or NO_2 and the degradation products of tertiary amines. However, primary amines can also indirectly form nitrosamines. For example, it has been shown that MEA, a primary amine, will react with NO_2 to form diethanolamine (DEA), which is a secondary amine. DEA can then undergo nitrosation to form nitrosodiethanolamine (NDELA), making the presence of DEA in the absorber or treated flue gas hazardous.

Nitramines can be formed from the reaction between primary, secondary, or tertiary amines with nitrogen oxides. They are less carcinogenic than nitrosamines but still potent (Spietz et al., 2017).

Concentrations of nitrosamines and nitramines reported in the 30% MEA pilot campaigns are stated in Table 8.

Table 8: Nitrosamine and nitramine concentrations in pilot campaigns

Pilot plant and reference	Nitrosamine and nitramine concentrations
TCM (Morken et al., 2014)	Solvent NDELA: 4.2 mg/l; Other nitrosamines in solvent below the limit of detection; Solvent methylnitramine: 2.12 mg/l Total nitrosamines in depleted flue gas below the limit of detection
TCM (Morken et al., 2017)	Solvent total nitrosamines: 306 mg/l; Solvent NDELA: 4.9 mg/l; Solvent Nitroso-N-(2-Hydroxyethyl)glycine: 235 mg/l; Solvent methylnitramine: 4.0 mg/l;

Pilot plant and reference	Nitrosamine and nitramine concentrations
	Total nitrosamines in depleted flue gas below the limit of detection
Amagger Bakke ARC (Neerup et al., 2023)	Depleted flue gas total nitrosamine: <0.004 mg/m^3; Depleted flue gas NDELA: 0.00011 mg/m^3 Other nitrosamines in flue gas below the limit of detection

Only two nitrosamines and one nitramine were recorded in quantifiable concentrations in the pilot studies shown in Table 8. These concentrations were measured either in the solvent or in the flue gas immediately after the acid and water wash sections so do not account for dispersion from the stack.

There is currently only one environmental assessment level (EAL) by the EA for a nitrosamine or nitramine. It is the long term EAL for N-nitrosodimethylamine (NDMA): 0.2 ng/m^3 as an annual average. NDMA was monitored for in the pilot campaigns described above, but its levels were below the limit of detection.

After thermal reclaiming in Morken et al. (2017) the total concentration of nitrosamines in the solvent was reduced, suggesting that reclaiming is an effective strategy to prevent their build-up. Neerup et al. (2023) demonstrated that the use of acid and water wash sections reduced the concentration of nitrosamines in the depleted flue gas.

Nitrosamine and nitramine emissions at the CC facility will be mitigated by periodic thermal reclaiming, water wash sections and dispersion from the stack.

The process will be bunded to minimise the impact of a leak from the process. Appropriate PPE will also be used in the event of a leak to mitigate against volatile emissions of nitrosamines and nitramines from the solvent since they might be hazardous even in small quantities.

C.4.3.2 Ammonia

With a vapour pressure of 8,600 hPa at 20°C, ammonia is a highly volatile product that has been demonstrated to be the dominant product of degradation (Morken et al., 2017). It is thought to be an oxidative degradation product resulting from the reaction of MEA with oxygen in the flue gas. This means it is produced in the absorber. Due to its extremely high volatility ammonia is likely to be a contaminant in the depleted flue gas. It is unlikely to leave the absorber in the rich amine solution.

The hazardous properties associated with ammonia are listed below in Table 9.

Table 9: Hazardous properties of ammonia.

Hazard	Hazard Statement
Flammable gases	H221: Flammable gas
Gases under pressure	H280: Contains gas under pressure, may explode if heated.
Skin corrosion	H314: Causes severe skin burns and eye damage
Serious eye damage	H314: Causes severe skin burns and eye damage
Acute aquatic hazard	H400: Very toxic to aquatic life

Hazard	**Hazard Statement**
Long-term aquatic hazard	H411: Toxic to aquatic life with long lasting effects
Acute toxicity, inhalation	H331: Toxic if inhaled

Source: CF Fertilisers UK Limited

MEA shares some of the hazardous properties listed above. The properties associated with ammonia but not MEA are that it is a flammable gas and is a long-term aquatic hazard.

Ammonia concentrations observed in the 30% MEA pilot campaigns reviewed are listed in Table 10.

Table 10: Ammonia concentrations in depleted flue gas

Pilot plant and reference	**Ammonia concentration in depleted flue gas**
TCM (Morken et al. 2017)	9 – 96 mg/m^3
Amager Bakke (Neerup et al. 2023)	0.21 – 4.04 mg/Nm^3
UKy-CAER Thompson et al. (2017)	39 – 87 mg/m^3

From our review of the TCM and UKy study, the high concentrations of ammonia recorded were associated with startup activities. As degradation is dependent on operating conditions and flue gas composition, the concentration in which these chemicals have been reported is arbitrary to some extent (Buvik et al., 2021). Degradation is time dependent so the concentration of degradation products during pilot campaigns is not necessarily representative of what would be produced during long term operation. For the CC facility, the water wash will be designed to ensure that the emissions of ammonia comply with the ELV of 15 mg/Nm^3 proposed in the EP application.

In addition, the Dispersion Modelling Assessment has quantified the impact of emissions of ammonia from the CC facility on the local environment. This has shown that the stack height is suitable to disperse emissions of ammonia and that the impact at ground level on air quality when compared to the AQALs for the protection of human health can be screened out as insignificant.

In the event of a leak from the absorber appropriate PPE would be required to prevent acute toxicity from inhalation of ammonia.

C.4.3.3 Aldehydes

Aldehydes are also a primary product from the degradation of MEA in the presence of oxygen. The aldehydes which have been identified to date in flue gas emissions in pilot plant studies are:

- formaldehyde;
- acetaldehyde;
- hydroxy acetaldehyde; and
- amino acetaldehyde.

The Dispersion Modelling Assessment has quantified the impact of emissions of aldehydes and compared the impact to the EAL for formaldehyde given this is the only aldehyde with an EAL. This has shown that the stack height is suitable to disperse emissions of aldehydes and that the impact at ground level on air quality when compared to the AQALs for the protection of human health can be screened out as insignificant.

C.4.3.4 Summary of all hazardous properties associated with used MEA

Table 11 summarises all of the hazardous properties associated with MEA and its significant degradation compounds. Vapour pressures have also been included to indicate volatility of these compounds. The volatility of these compounds impacts the degree to which they might be released as emissions to air in the event of a leak.

Table 11: Summary of the hazardous properties associated with used MEA solvent

Compound	Hazardous properties	Vapour pressure	Mitigation factors at CC facility
MEA (rich and lean)	Flammable liquids (increases above 86°C); Acute toxicity (oral, inhalation and dermal); Skin corrosion (increases with temperature and CO_2 loading); Serious eye damage; Acute aquatic toxicity.	0.5 hPa at 20°C (pure MEA)	Stainless steel construction; bund; stack height; water wash.
Ammonia	Flammable gases; Gases under pressure; Skin corrosion; Serious eye damage; Acute aquatic hazard; Long-term aquatic; hazard Acute toxicity.	8,600 hPa at 20°C (high)	Stainless steel construction; stack height; water wash.
Nitrosamines and nitramines	Carcinogenicity; Acute toxicity; Acute aquatic toxicity.	Compound specific. NDMA: 1.3 hPa at 20°C; NDELA: 0.0007 hPa at 20°C; Nitroso-HeGly: Unknown; Methylnitramine: unknown.	Stack height; water wash; bund; thermal reclaiming.

Source: Fichtner and PubChem database

The mitigation factors described in Table 11 are expected to be sufficient to minimise the hazardous properties associated with used (and fresh) MEA at different stages in the utility cycle.

The process will be bunded to minimise the potential impacts of a leak. However, additional mitigation measures of PPE and spill kits would also be required in the event of a leak to ensure the safety of operators.

C.5 Conclusions

As set out within this Appendix, a review of available information on pilot campaigns and trials on demonstrator carbon capture systems indicates that changes to the hazardous properties of MEA during the capture process are expected as follows.

- MEA becomes more corrosive when loaded with CO2 and at higher temperatures. Consequently, amine contained in the stripper and reboiler is considered to be hazardous as it has a higher corrosivity. With the use of stainless steel construction materials and periodic thermal reclaiming this is not expected to be a risk to the process.

- MEA becomes more flammable at temperatures above its flash point which is 86oC. This hazard will be contained within the process during normal operation.
- Degradation of MEA can lead to the formation of nitrosamines and nitramines. These are volatile compounds which can be carcinogenic even in small quantities. With periodic thermal reclaiming and the use of water wash for gases this is not expected to be a concern for the process during normal operation.
- Degradation of MEA is likely to lead to the formation of ammonia which is volatile, corrosive, acutely toxic, an irritant and toxic to aquatic life. Aldehydes will also be a primary degradation product. Again, with the use of water wash for gases this is not expected to be a concern for the process during normal operation.

Abatement techniques in the literature were demonstrated to be effective in removing all of the hazards highlighted above. Consequently, it is understood that these hazards can be mitigated by integrating the appropriate mechanisms within the overall design of the CC facility. Only in the event of a leak from the process would there be potential for harm. Therefore, the containment of leaks from the CC facility will be essential to managing these hazards.

C.6 References

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D Plans and drawings

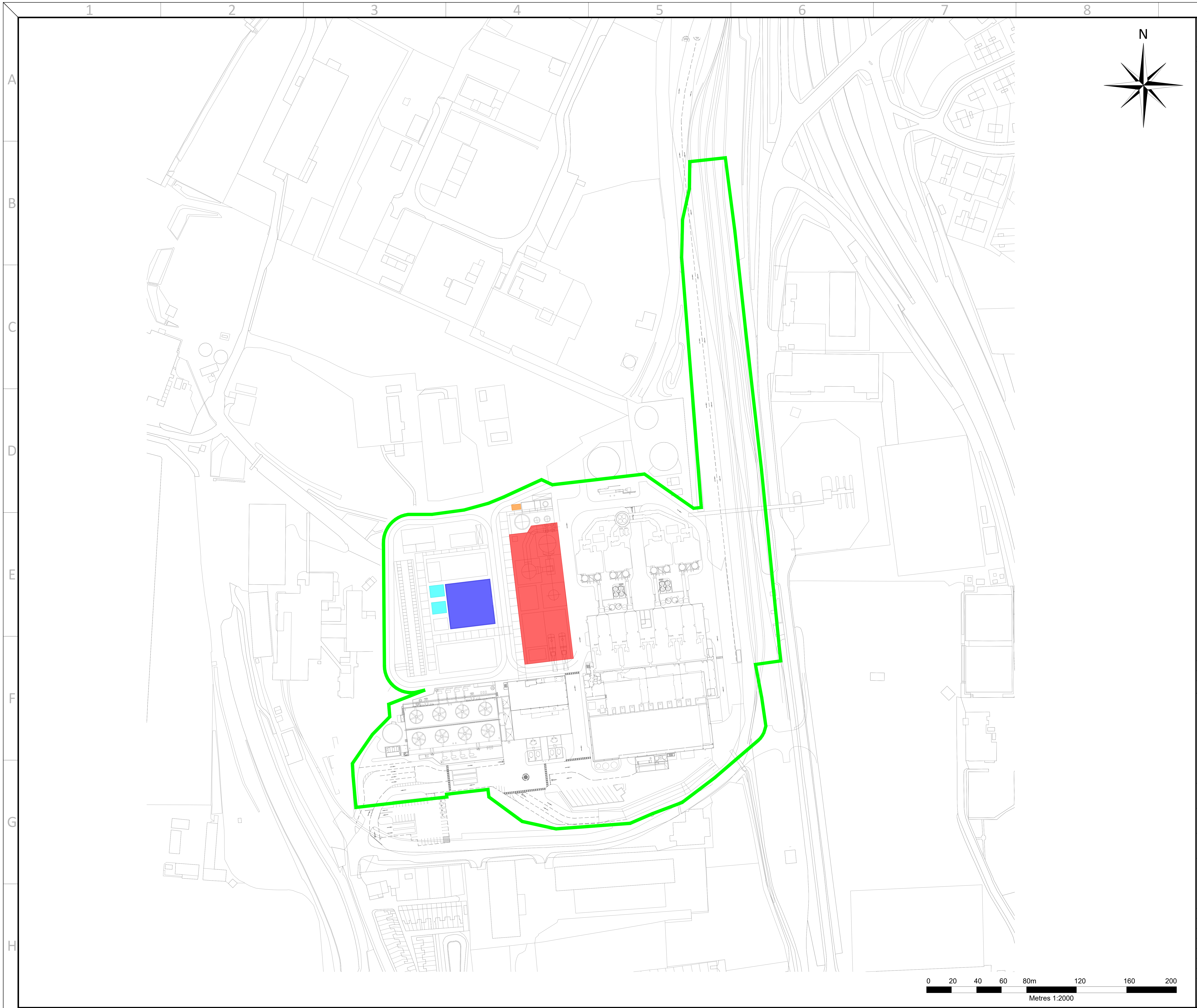
D.1 CO_2 containment facilities

D.2 Indicative process schematic

D.3 Hazardous materials storage

D.4 Site access and egress points

D.5 Indicative drainage flows



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🟥	CO₂ REMOVAL
🟦	COMPRESSOR
▬	DEHYDRATION/DEOXYGENATION
🟧	CO₂ METERING

REV.	DETAILS OF REVISION	DRAWN	CHKD	APR	DATE
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PROJECT:
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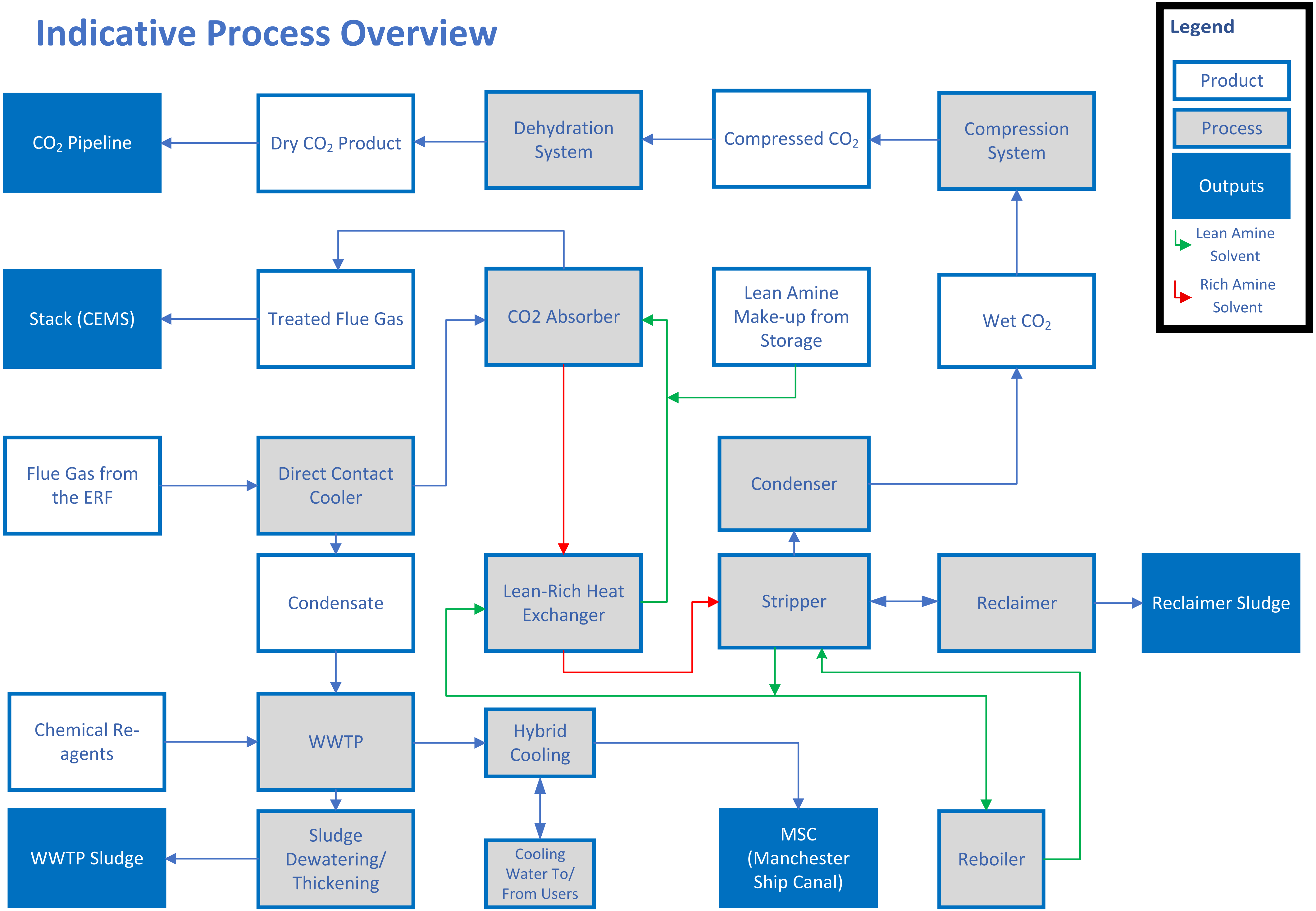
Indicative Process Overview



CO_2 Pipeline

Dry CO_2 Product

Dehydration System

Compressed CO_2

Compression System

Stack (CEMS)

Treated Flue Gas

CO2 Absorber

Lean Amine Make-up from Storage

Wet CO_2

Flue Gas from the ERF

Direct Contact Cooler

Condenser

Condensate

Lean-Rich Heat Exchanger

Stripper

Reclaimer

Reclaimer Sludge

Chemical Re-agents

WWTP

Hybrid Cooling

MSC (Manchester Ship Canal)

Reboiler

WWTP Sludge

Sludge Dewatering/ Thickening

Cooling Water To/ From Users

Legend

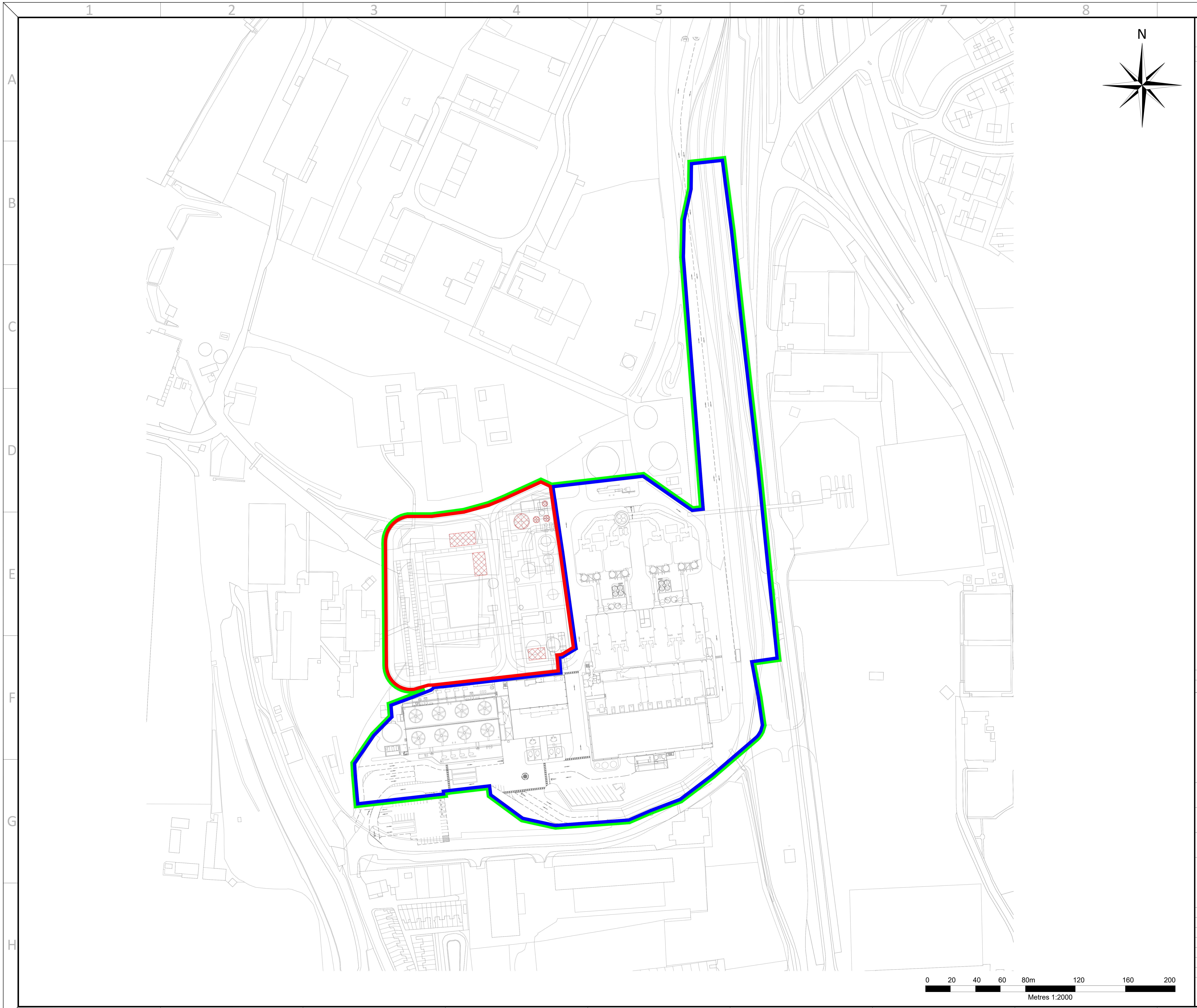
Product

Process

Outputs

Lean Amine Solvent

Rich Amine Solvent



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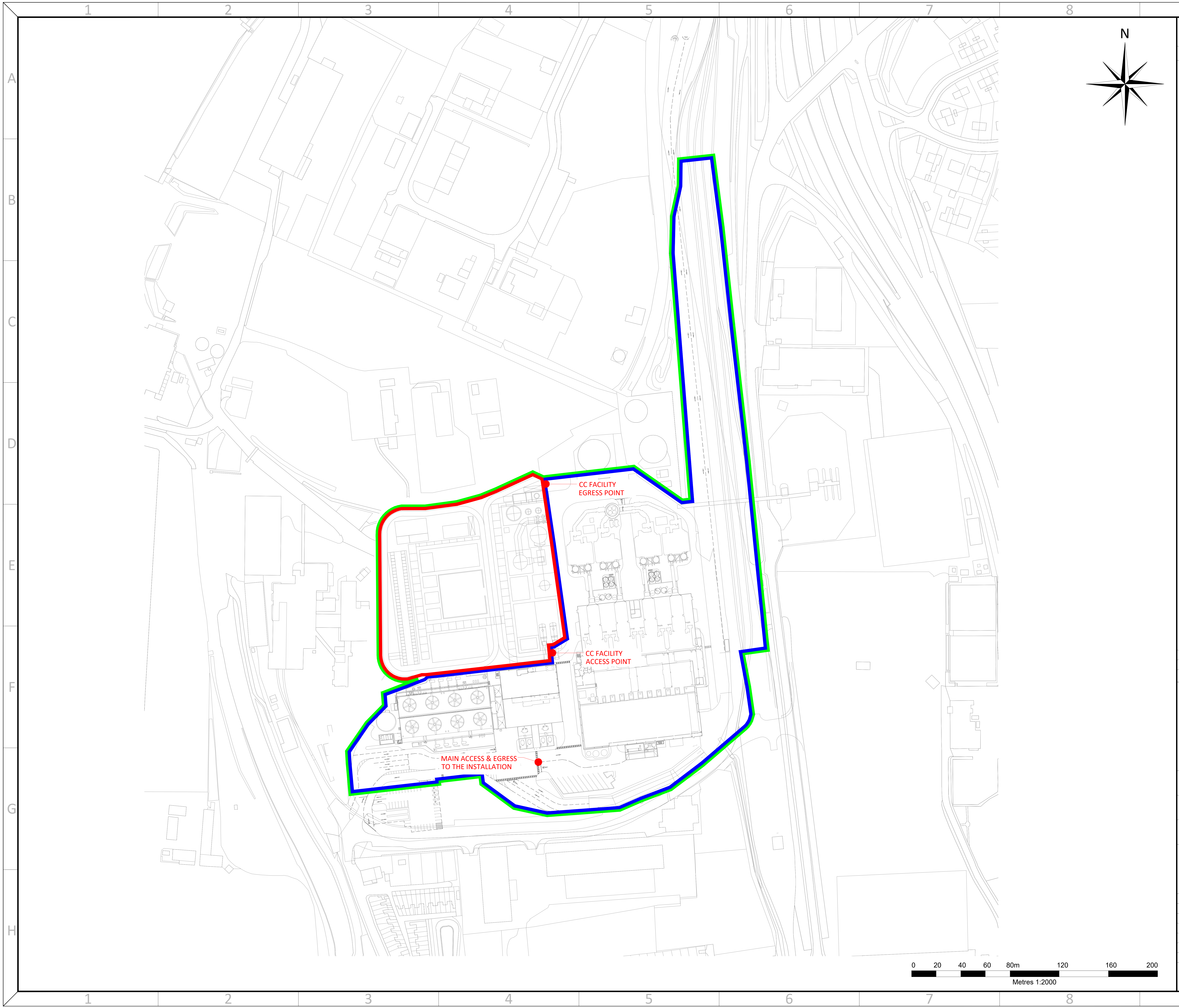

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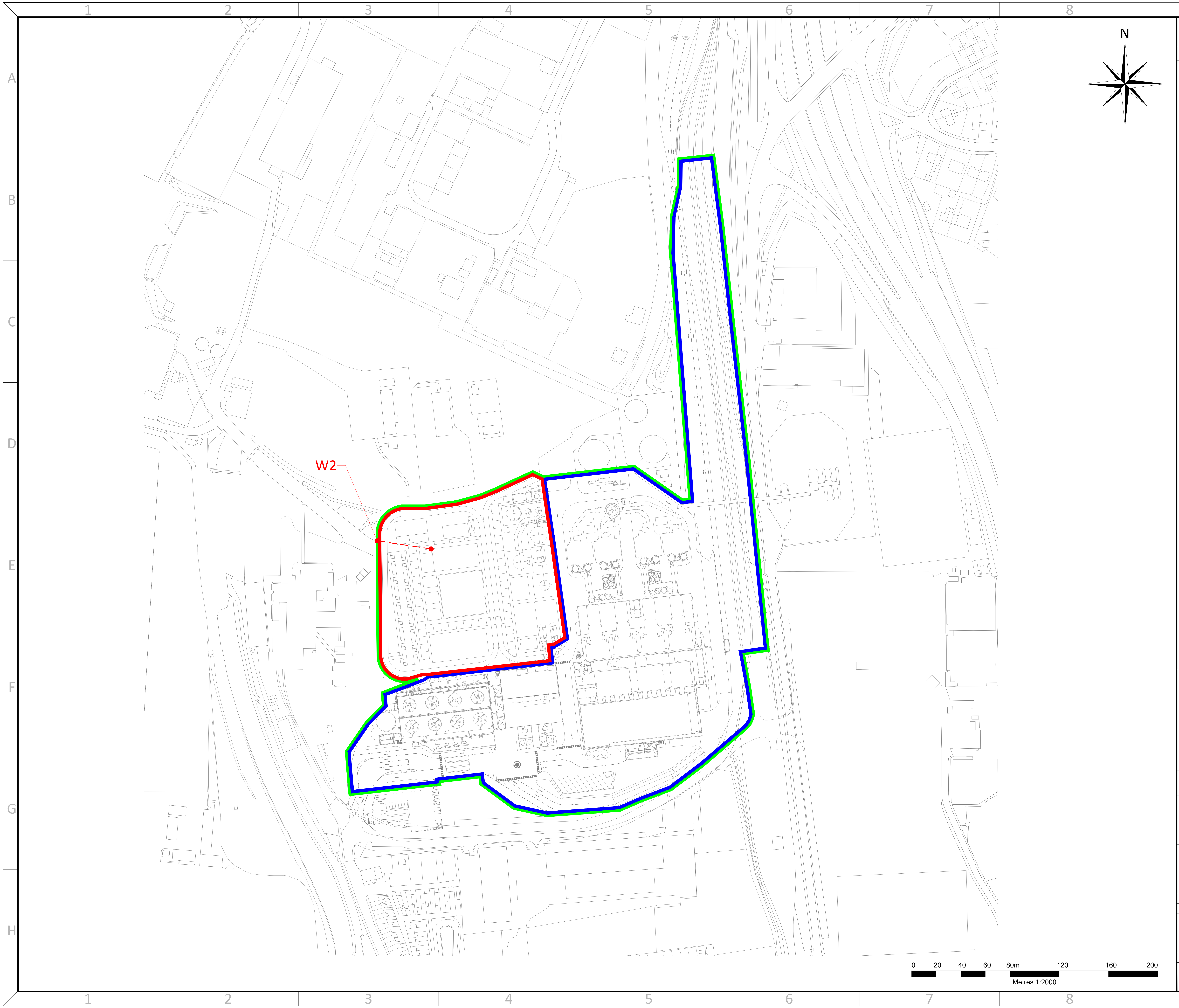

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