Application of a Transformational UKy 3 Ton/Day CO_2 Capture System at a Steel Process Plant DE-FE0032133

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http://uknow.uky.edu/research/unique-public-private-research-consortium-established-caer-co2-capture-pioneers

2023 Carbon Management Research Project Review Meeting
August 28-September 1, 2023

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Project Objective

Demonstrate the UK CO_2 capture process at Nucor Steel Gallatin treating electric arc furnace evolved gas with a CO_2 concentration of ~1.5 vol%

Performance Dates: 4/25/2022-1/31/2026

BP1

4/25/22-1/31/24

- Design
- Contractor selection

BP2

2/1/24-1/31/25

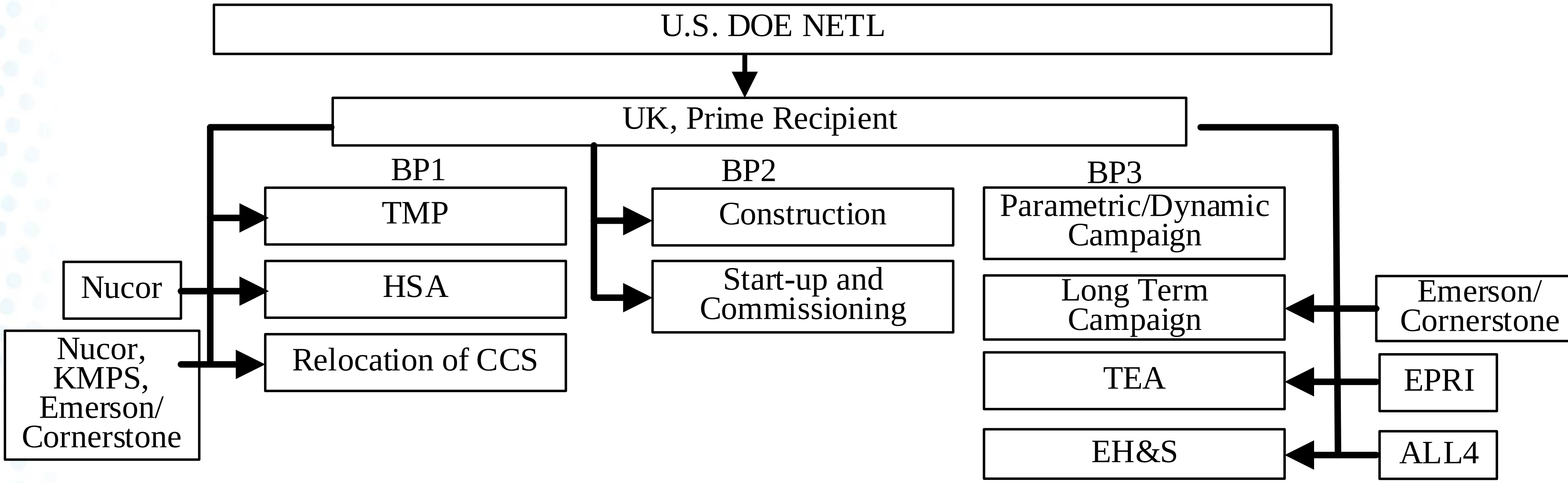
- Site Prep
- Module Erection
- Tie-in at Nucor

BP3

2/1/25-1/31/26

- Evaluation
- Data Analysis
- Reporting

Project Team and Funding



	DOE-NETL	Cost Share	Total
Total	**$4,999,965**	**$1,250,523**	**$6,250,488**
Percent Share	**80%**	**20%**	**100%**

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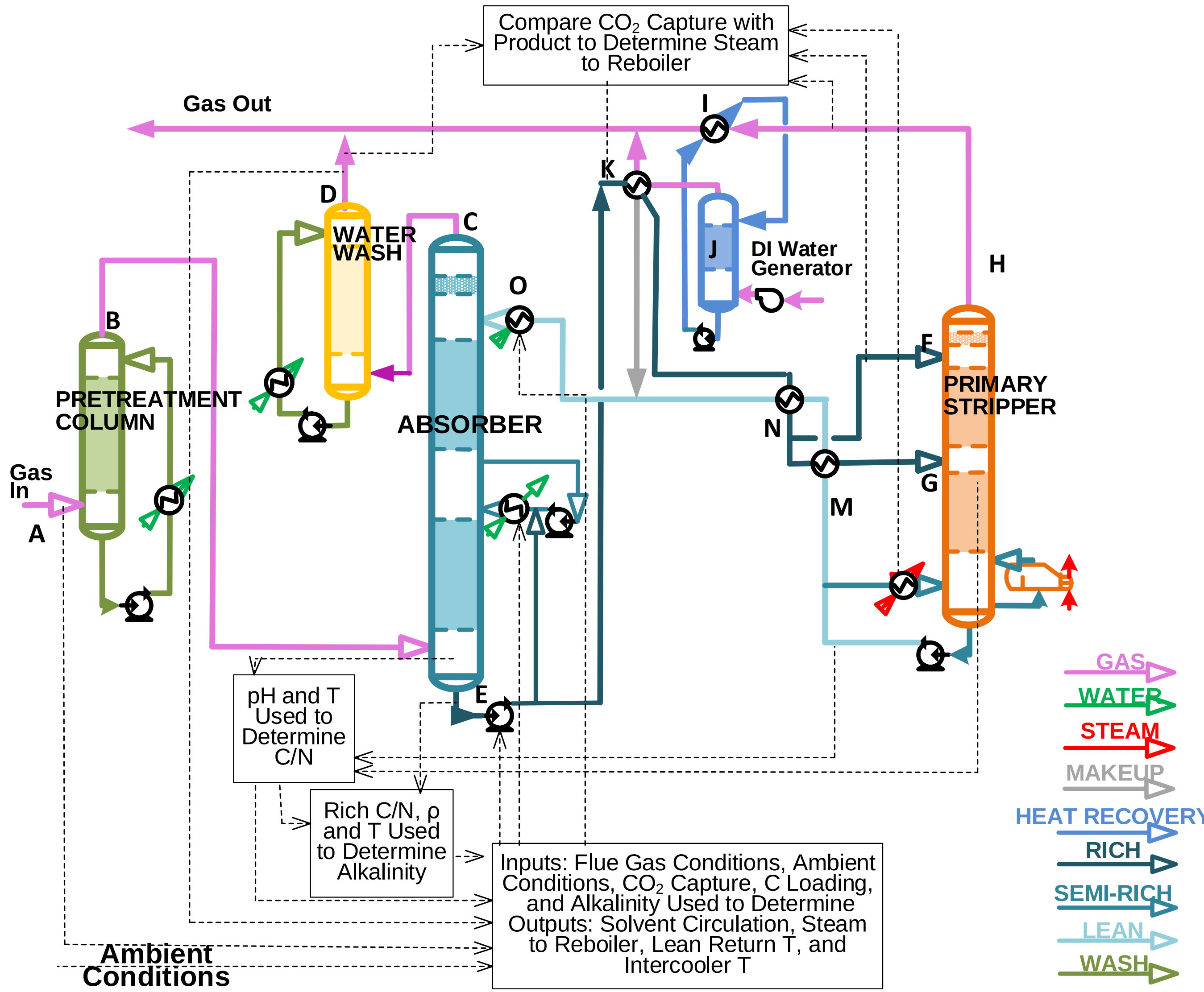
Technology Background

1. Absorber with T and Absorption Profile Control
2. Split Rich Stripper Feed
3. Forward-feed Advanced Process Control



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Technology Background

UK Field Pilot CO_2 Capture Unit

MEA Parametric Campaign

- ~1300 hours run with MEA
- Process can easily capture 90% of CO_2
- Solvent regeneration energy of 1200–1750 BTU/lb CO_2-captured, ~13% lower than Reference Case 10 (RC 10)

MEA Long-term Campaign

- Process performance is dependent on ambient conditions
- Channel flow observed in absorber
- Thermal compression benefits realized when lean/rich exchanger approach temperature < 20 °F
- Recirculating cooling water is 3-9 °F cooler compared to a conventional cooling tower at the same ambient conditions
- Degradation was comparable to other published MEA pilot studies under similar conditions
- Impact of the secondary air stripper on solvent oxidative degradation was negligible
- Nitrosamines were not found in emissions above the limits of detection during the MEA campaign

H3-1 Parametric Campaign

- ~1500 hours run with H3-1
- Solvent regeneration energy of 900–1600 BTU/lb CO_2-captured, ~36% lower than RC10
- Secondary air stripper performs as expected with partial CO_2 recycling (>20% of CO_2 captured) demonstrated to enhance gaseous CO_2 pressure at the absorber inlet.

H3-1 Long-term Campaign

- 90% CO_2 capture and low solvent regeneration energies are possible with a range of solvent concentrations
- Selenium concentration exceeded RCRA limit
  - Thermal reclaiming is effective to remove RCRA elements from the solvent
- H3-1 is ~15-20% less corrosivity than MEA
- H3-1 solvent loss is ~20% less than MEA
  - Most of the solvent loss due to entrainment from columns
- Nitrosamines were detected in emissions during the H3-1 campaign
- Secondary air stripper does not contribute to solvent oxidative degradation

UK Solvent Parametric Campaign

- ~850 hours run with CAER solvent
- Solvent regeneration energy consistent with findings at bench scale

UK Solvent Long-term Campaign

- The MBT additive/inhibitor is effective reducing corrosivity and degradation
- Nitrosamine and aldehyde emissions were insignificant and comparable to the MEA campaign
- Thermal reclaiming is effective to maintain levels of RCRA elements in the solvent below the hazardous waste limits
- Absorber is overdesigned and maximum solvent absorption is attained

Other Advanced Solvent Campaigns

- Significant solvent regeneration energy differences with similar CO_2 caputure is not observed
- Cold absorber bottom T favors higher rich loading

UK Solvent

- $6.50/kg chemical cost
- Hindered primary amine blend, no stable nitrosamine formation
- >7500 experimental hours at bench and engineering scales
- NG- and coal-fired flue gas evaluations
- 3-20 vol% CO2 inlet concentration evaluations
- Aspen Plus model validated by engineering scale data
- Solvent regeneration energy as low as 1040 BTU/lb CO2
- Make up rate of 0.6 kg/tonne CO2

UK Bench CO_2 Capture Units

H3-1 Solvent Campaign

- H3-1 Solvent Performance: ~27% reduction in solvent regeneration energy, 35-45% reduction in circulation rate, 1.5X cyclic capacity, low degradation, higher viscosity and lower surface tension compared to 30 wt% MEA

CCSL Solvent Campaign

- CCSL Solvent Performance: ~30% reduction in solvent regeneration energy, 40% reduction in circulation rate, 2X cyclic capacity, low degradation, higher viscosity and lower surface tension compared to 30 wt% MEA

Process Modifications

- Absorber T control via discretized packing In-situ liquid distribution
- Open tower compact absorber with spray (50 µm droplets) leads to enhances mass transfer by 4X
- Staged absorber and stripper feeds
- CO_2 preconcentrating membrane results in increased rich carbon loading by 17% and a 25% reduction in regeneration energy
- Solids circulation solvent recovery system reduces amine emissions by 50%
- ~100% CO_2 capture with dual-loop process
- Heat transfer packing
- Acoustic packing
- Hydrophilic/phobic packing
- De-watering membrane

Lab CCS

Nitrosamine Removal

- 50-90% nitrosamine removal demonstrated with carbon sorbent

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Technology Background

Technical Advantages

- Simple, solvent-agnostic process
- UK hindered primary amine solvent → no stable nitrosamine formation
- Split rich stripper feed → reduced solvent regeneration energy requirement
- Advanced, feed-forward process controls → real-time solvent quality knowledge and automatic set points for energy minimization

Technical Challenge

- Low CO_2 concentration (~1.5 vol%) → low L/G → possible maldistribution on packing

Project Challenge

- Repurpose existing equipment

Site Selection

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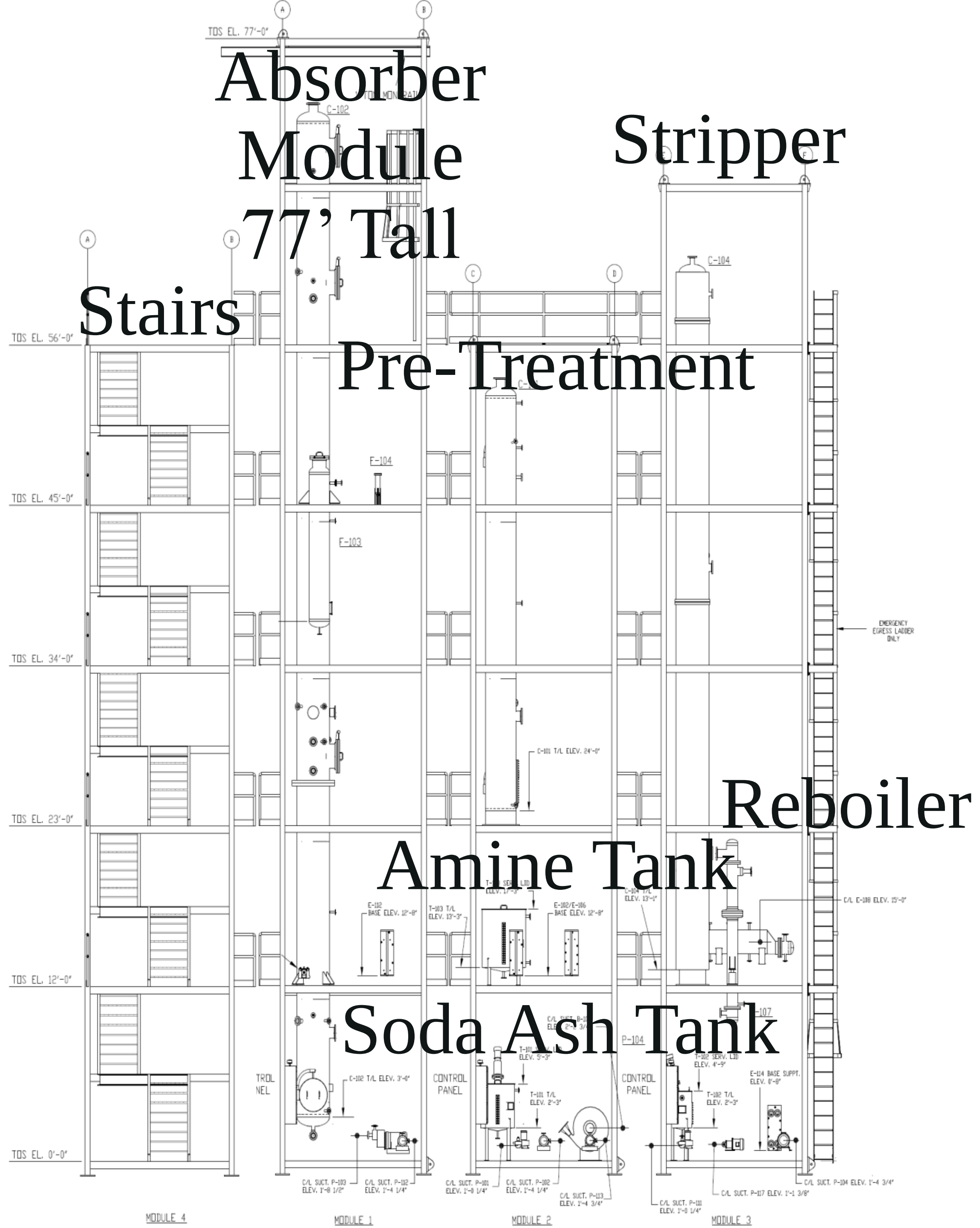
Repurpose Existing Modules



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Repurpose Existing Columns and HX

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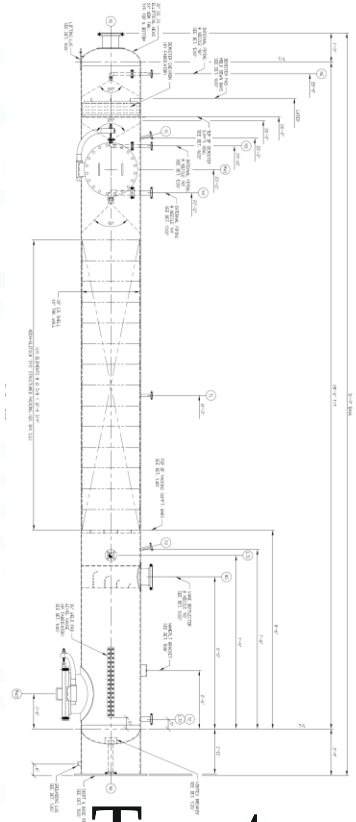
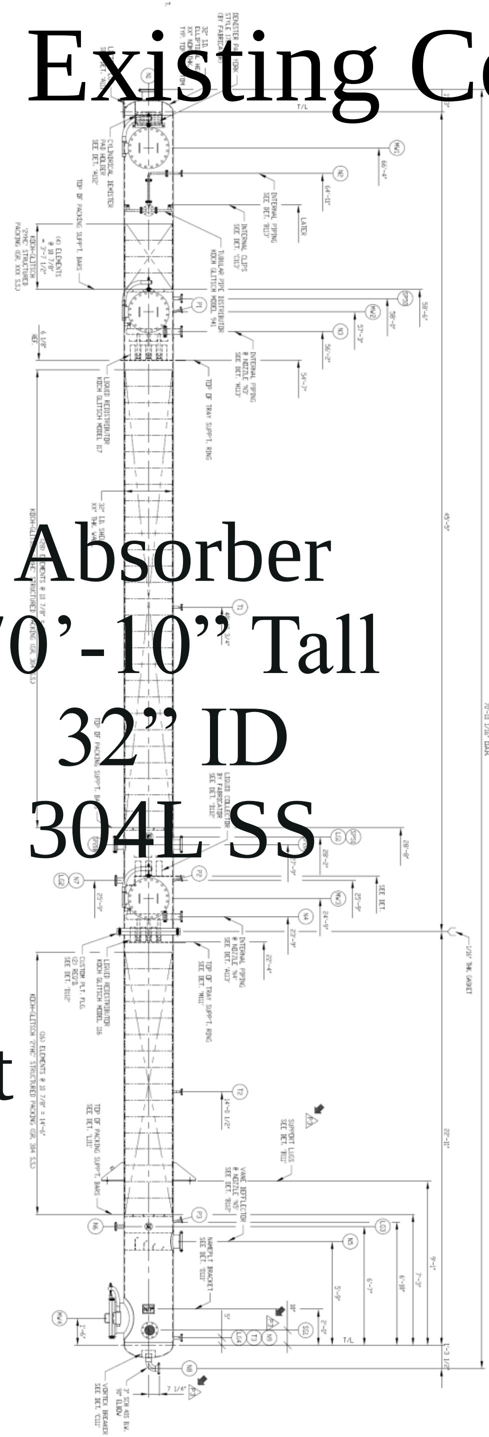
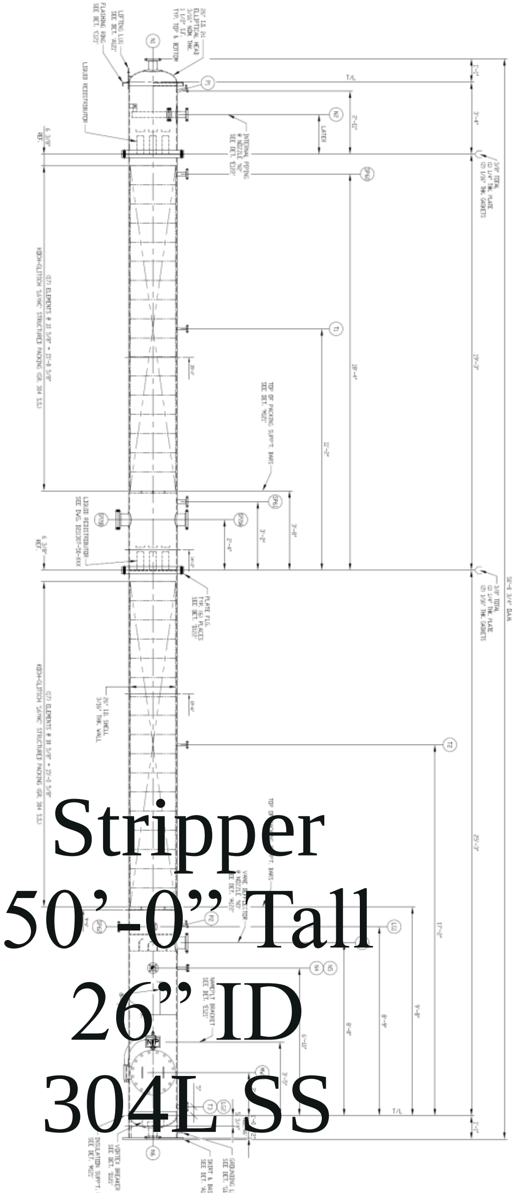


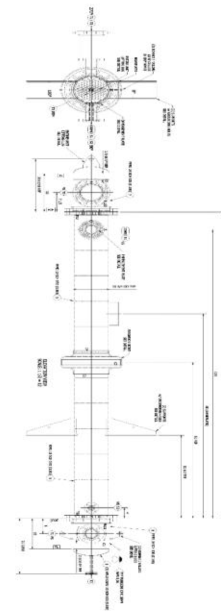
Pre-Treatment
28’-6” Tall
30” ID
304L SS



Absorber
70’-10” Tall
32” ID
304L SS

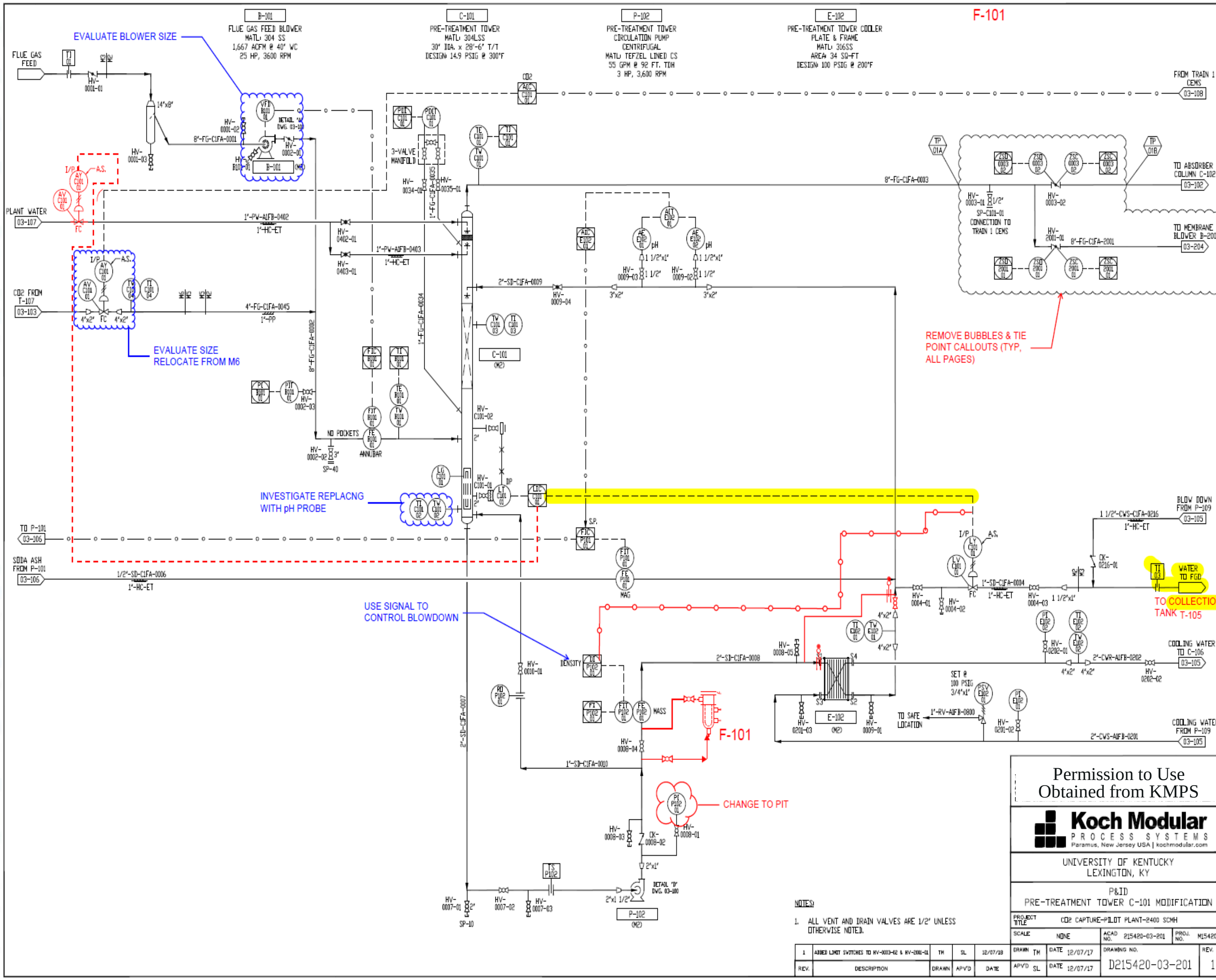


Stripper
50’-0” Tall
26” ID
304L SS



Reboiler
Shell &
Tube
Forced
Solvent
Circu-
lation

Line by Line P&ID Review



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Experimental Plan

	Length of Test Period	Effectiveness Evaluated By	Variables and Important Process Parameters	Instrument/Analytical Methods Employed
Parametric Testing for Optimum Operating Conditions	5 Months, 8 Hours per Condition with 2-3 Hours for Stabilization	Capture Efficiency	Lean Solvent Flowrate and Return	Pressure Transducer, Thermocouple, RTD, Mass Flowmeter, Density, pH, Conductivity, Pitot Tube for Gas Flow, Power Meter
		Energy Consumption	Flue Gas Flowrate and Temperature	
		Gaseous Pressure Drop	Lean Solvent Physical Property	
		Overall Absorber CO_2 Transfer Flux	Inter-stage Cooling Duty	
		Rich Carbon Loading at Absorber Outlet	Stripper Pressure and Reboiler Temperature of Primary Loop	Gas Analyzer for $CO_2/H_2/O_2$
		Temperature Difference between Stripper Top Gas and Bottom Lean	Absorber Temperature Profile of the Primary Loop	Titrator for Alkalinity and Carbon Loading, GC-MS and HPLC for Amine
Dynamic Testing with/out Feed-forward Process Control	1 Month in total, 4 Hours per Condition	Capture Efficiency	Lean Fowrate	Gas Analyzer for $CO_2/H_2/O_2$
		Temperature Difference between Stripper Top Gas and Bottom Lean Exiting Streams	Stripper Pressure and Heat Flux to Reboiler of the Primary Loop	Pressure Transducer, Thermocouple, Flowmeter, Density, pH, Conductivity, Power Meter, Gas Flowmeters
		Reboiler Specific Duty	Flue Gas Flowrate	Valve Response, Steam Flow Response, and in-line Carbon Loading
		Ramp Rate	CO_2 Concentration at Absorber Inlet	
Long-term Campaign	3 Months with a Two-Shift 10 Operational Hours per Day, and One Month Continueous Run	Capture Efficiency	Lean Flowrate	Gas Analyzer for $CO_2/H_2/O_2$
		Temperature Difference between Stripper Top Gas and Bottom Lean Exiting Streams	Stripper Pressure and Heat Flux to Reboiler of the Primary Loop	Pressure Transducer, Thermocouple, Flowmeter, Density, pH, Conductivity, Power Meter, Gas Flowmeters
		Reboiler Specific Duty	Flue Gas Flowrate	Valve Response, Steam Flow Response, and in-line Carbon Loading
		Ramp Rate and Operability to Achieve 95+% Capture Including Ambient Condition and External Load Changing	CO_2 Concentration at Absorber Inlet	

Technical Approach

Technology	Performance Matrix	Impact on CCS Cost (CAPx and OPEx)
Advanced Process Control Strategy	-Response time <5 minutes -Average performance >90% of steady state operation	-No impact on CAPx -Reduction of steam extraction during cycliclic operation -Reduction of solvent degradation from overshooting stripper P and reboiler T
Discretized Absorber Packing with Matched Solvent Physical Properties	-Bulge temperature <150 °F at L/G =3.5 -Average mass transfer coefficient >1.5x of traditional configuration -Reduction of column differential pressure by up to 5% compared to traditional arrangement -Solvent carbon cyclic capacity >1 mol/kg solvent -Elimination of liquid maldistribution	-Reduction of CAPx due to short packing requirement -Reduction of steam extraction due to improved solvent cyclic capacity and lower sensible heat requirement -Reduction of auxiliary power consumption resulting from shorter column and lower gas pressure drop
Split Rich Primary Stripper Feed	-Primary stripper top-to-bottom dT > 35 °F -Reduction of reboiler specific duty by >15% compared to traditional stripper configuration	-Increase of CAPx due to split of one L/RHXER into two for easy system control and additional associated piping, but should be negligible due to same heat load maintained -Reduction of steam extraction by 15%

Project Milestones

BP	Description	Planned Completion Date	Actual Completion Date
1	Project Kickoff Meeting Held	8/24/2022	5/31/2022
1	TMP Complete	8/24/2022	9/16/2022
1	Host Site Agreement (HSA) Complete	5/31/2023	5/24/2023
1	PDP Complete	9/30/2023	
1	Boiler Procurement Decision Point Meeting	8/31/2023	8/23/2023
1	General Contractor Selected	1/31/2024	
2	Nucor Site Prepared for Installation	4/3/2024	
2	CCS Installed at Nucor	8/1/2024	
2	Test Plan Complete	8/1/2024	
2	Commissioning Complete	1/31/2025	
3	Parametric/Dynamic Campaign Complete (Demonstrate 95% CO_2 capture efficiency and CO_2 product stream purity of ≥95%; quantify absorber performance and reboiler duty)	6/30/2025	
3	Long-term Campaign Complete (1000 hours showing optimized process conditions, dynamic stability and operability)	9/30/2025	
3	TEA Complete	10/31/2025	
3	EH&S Complete	10/31/2025	

Project Success Criteria

Completion of BP1 1) Contract in place with engineering design firm for CCS reconfiguration and relocation 2) Boiler specified and procured 3) Contract in place with general contractor for relocation of CCS
Completion of BP2 1) Commissioned CCS at Nucor Steel Gallatin Site 2) Acceptance of test plan
Completion of BP3 1) At least 2 months of engineering-scale testing campaign of three transformational CO_2 capture technologies at the Nucor Steel Gallatin Site 2) Demonstrated ≥95% CO_2 capture efficiency 3) Demonstrated CO_2 product stream purity of ≥95% 4) Techno-economic analysis showing Cost of Capture and Cost of CO_2 Avoided, calculated for gross CO_2 captured and net CO_2 captured 5) Attainment of TRL 6 of the three proposed transformational CO_2 capture technologies

Project Risks and Mitigation Strategies

Perceived Technical Risk	Mitigation Response Strategy
Severe liquid misdistribution due to L/G	- Redesign the liquid collector and distributor - Reconfigure the absorber with local pump-around
Narrow operating hydraulic window due to discretized packing arrangement	- Modify the interstage cooler duty - Reconsider the absorber temperature profile while the capture efficiency target is considered
Unstable operation of high-temperature L/R solvent heat exchanger (plate-n-frame) due to vapor generation	- Increase the flow throughput - Reconfigure with large gasket or replaced with Tube-n-Shell exchanger
Time required by the control scheme calculation block takes too long due to the complication of model with 100+ variable inputs for a fast process response time to be realized	- Simplified calculation logic will be developed and implemented while the reasonable accuracy is maintained
Degraded matchability between packing surface and solvent physical properties due to the accumulation of solvent impurities from flue gas and degradation over time	- Solvent quality control methods will be developed - In-situ packing cleaning will be evaluated

Current Status

1. Host Site Agreement Executed
2. PO issued to KMPS for CCS Island Design and kickoff meeting held
3. Burns & McDonnell selected as BOP Design Firm/PDP Preparation and Contract Under Negotiation

Lesson Learned

1. A mutually beneficial partnership between the CCS operations team and the host site is critical.
2. Costs of the advanced solvent need to be balanced with the savings from energy consumption.
3. Utilization of Engineering Procurement and Construction (EPC) services are important, and they must satisfy the requirements of the host site and the technology developer in a triangular relationship.
4. Advancing through the TRLs in steps is necessary and results must be fundamentally understood at each scale.

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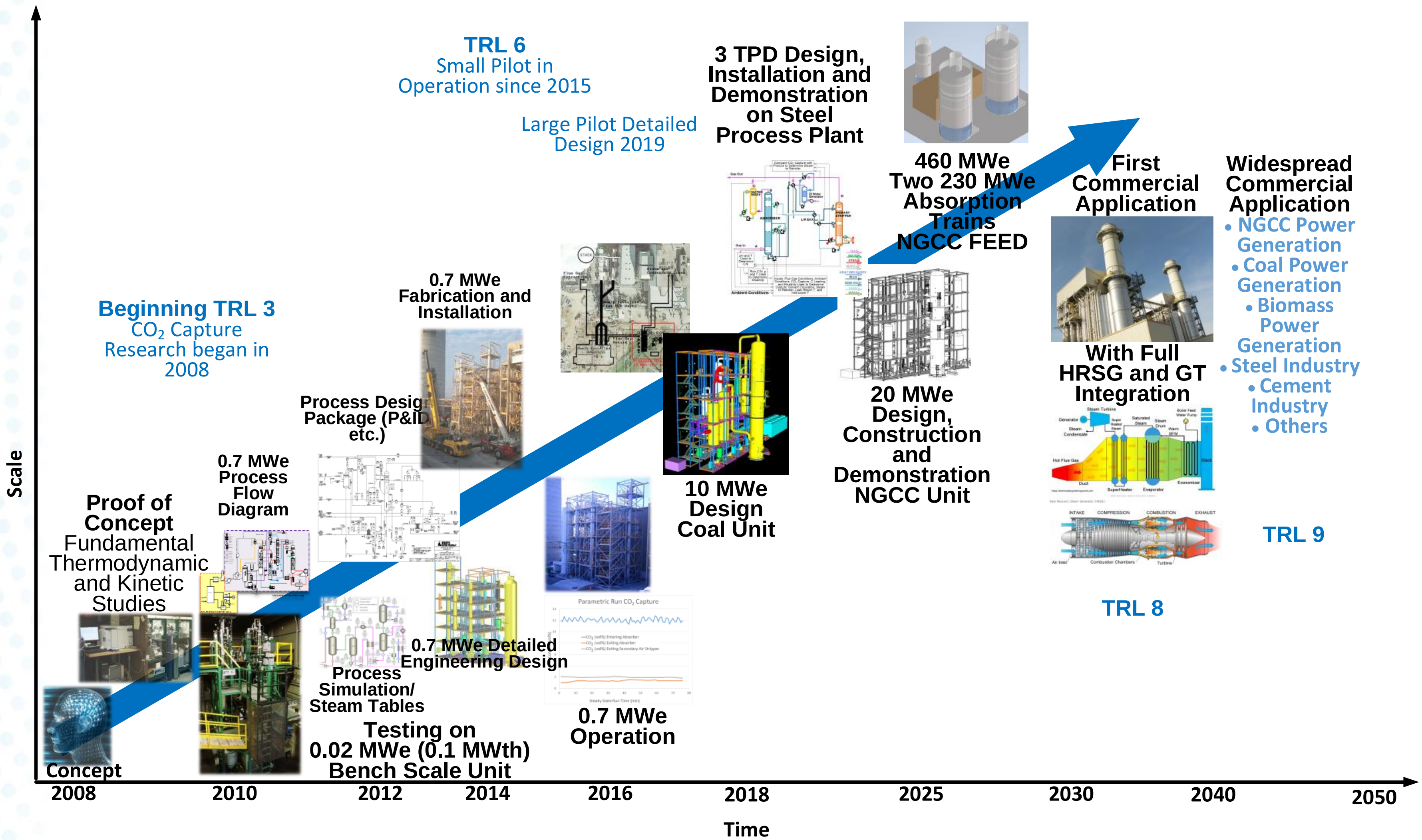
Future Development & Commercialization



Expected Output

- Experience and knowledge on low concentration CO_2 capture – performance, solvent management and dynamic operability
- Control strategy automatically maintains the target CO_2 capture efficiency while continuously minimizing the solvent regeneration energy.
- Full-scale deployment if the post-combustion CO_2 capture is feasible and cost effective

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Acknowledgements

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EPRI: Abhoyjit Bhown

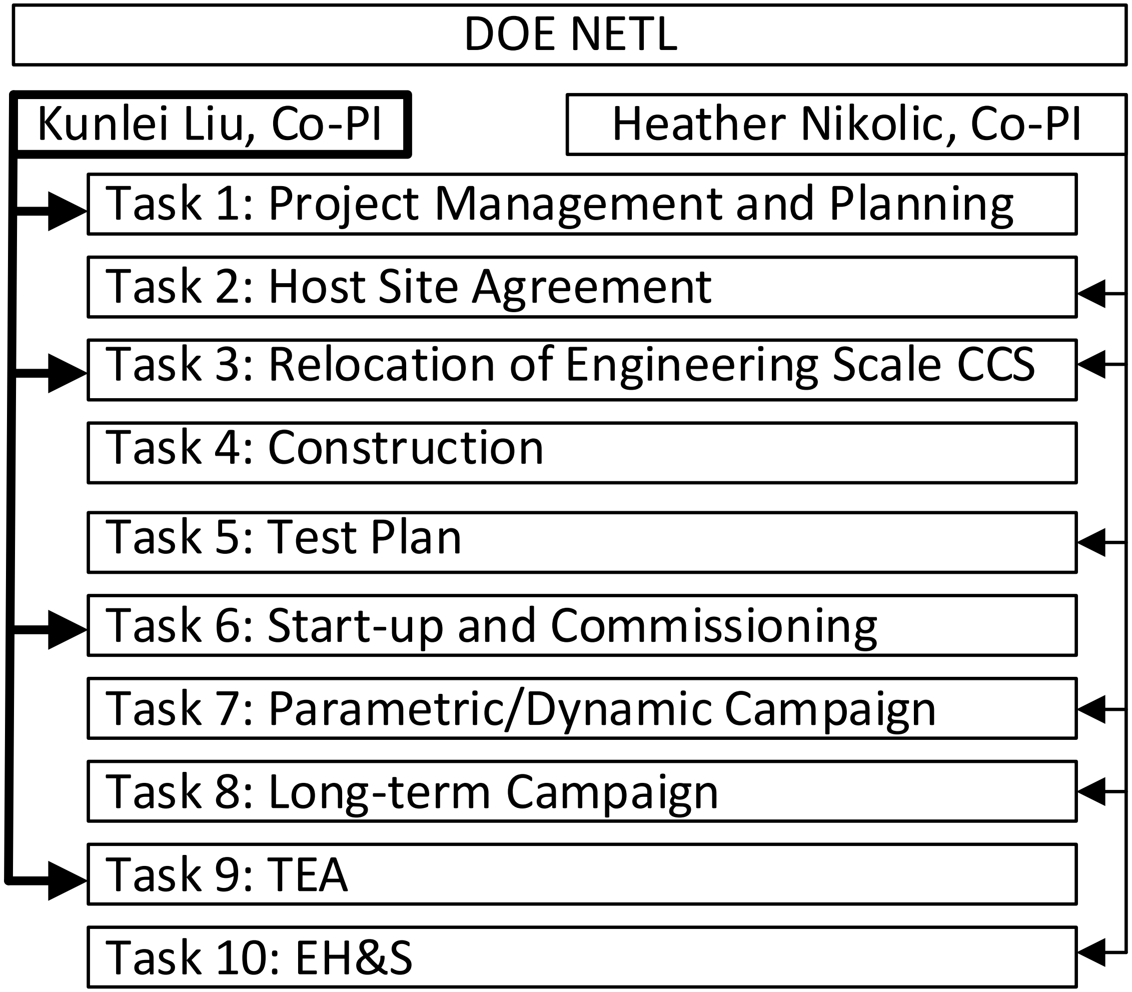
Emerson/Cornerstone: Vigen Biglari

ALL4: Karen Thompson

Targets for Cost Reduction

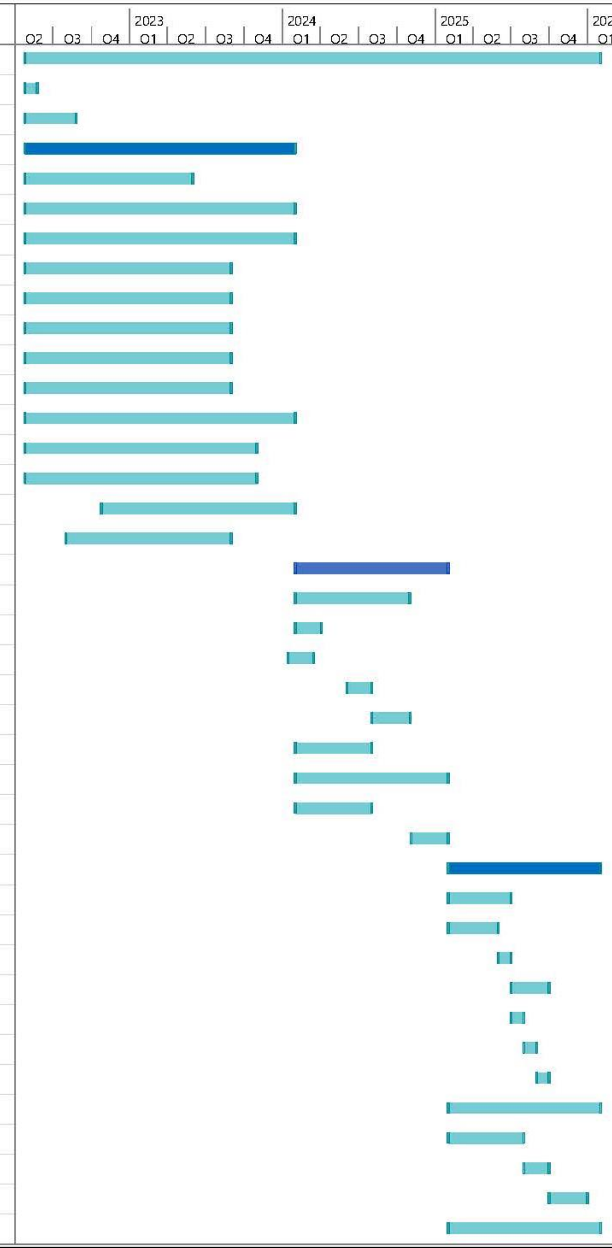
	B31A	B31B	UK Process
Capture Efficiency, %	N/A	90	95.0
Total Plant Cost, $/1000	566971	1281324	972500
Net Power Output at Design Condiiton, MMe	727	646	647
COE ($/MWh)	**43.3**	**70.8**	**61.5**
Fuel Costs	28.1	31.6	31.5
Variable Costs	1.7	5.6	4.4
Fixed Costs	3.6	8.6	6.6
Capital Costs	9.9	25.0	18.9
CO_2 Captured, lb/MWh		764	804
Cost of CO_2 Captured ($/tonne CO_2)		**79.6**	**49.9**
Reduction of CO_2 Capture from RC B31B			37%

Appendix: Organizational Chart



Appendix: Gantt Chart

Task Name	Start	Finish
1. Project Management and Planning	4/25/22	1/31/26
1.1. PMP	4/25/22	5/24/22
1.2. TMP	4/25/22	8/24/22
Budget Period 1	**4/25/22**	**1/31/24**
2. HSA	4/25/22	5/31/23
3. Relocation of Engineering Scale CCS	4/25/22	1/31/24
3.1. Reconfiguration	4/25/22	1/31/24
3.1.1. Absorber Internals	4/25/22	8/31/23
3.1.2. Split Rich Stripper Feed	4/25/22	8/31/23
3.1.3. Advanced Control Strategy	4/25/22	8/31/23
3.1.4. Process Simplification	4/25/22	8/31/23
3.2. Boiler	4/25/22	8/31/23
3.3. Site Survey and Preparation	4/25/22	1/31/24
3.4. Deconstruction and Removal Planning	4/25/22	10/31/23
3.5. Shipping Preparation	4/25/22	10/31/23
3.6. General Contractor Selection	10/25/22	1/31/24
3.7. HAZOP Evaluation	8/1/22	8/31/23
Budget Period 2	**2/1/24**	**1/31/25**
4. Construction	2/1/24	10/31/24
4.1. Foundation	2/1/24	4/3/24
4.2. Decommissioning and Shipping	1/15/24	3/15/24
4.3. Installation	6/4/24	8/1/24
4.4. Tie-ins	8/2/24	11/1/24
5. Test Plan	2/1/24	8/1/24
6. Start-up and Commissioning	2/1/24	1/31/25
6.1. Commissioning Plan	2/1/24	8/1/24
6.2 Start-up and Commissioning	11/4/24	1/31/25
Budget Period 3	**2/1/25**	**1/31/26**
7. Parametric/Dynamic Campaign	2/1/25	6/30/25
7.1. Absorber Packing Performance	2/1/25	5/31/25
7.2. Reboiler Specific Duty	6/1/25	6/30/25
8. Long-term Campaign	7/1/25	9/30/25
8.1. System Dynamic Stability and Operability	7/1/25	7/31/25
8.2. Reboiler Specific Duty Minimization	8/1/25	8/31/25
8.3. Packing Operability under Cyclic Operating Environment	9/1/25	9/30/25
9. TEA	2/1/25	1/31/26
9.1. Modeling	2/1/25	7/31/25
9.2. Equipment Sizing	8/1/25	9/30/25
9.3. Analysis	10/1/25	12/31/25
10. EH&S Risk Assessment	2/1/25	1/31/26



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