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

2024 FECM/NETL Carbon Management Research Project Review Meeting
August 5-9, 2024

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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: 4/25/2022-11/30/2026

BP1

4/25/22-11/30/24

- Design
- Contractor selection

BP2

12/1/24-11/30/25

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

BP3

12/1/25-11/30/26

- Evaluation
- Data Analysis
- Reporting

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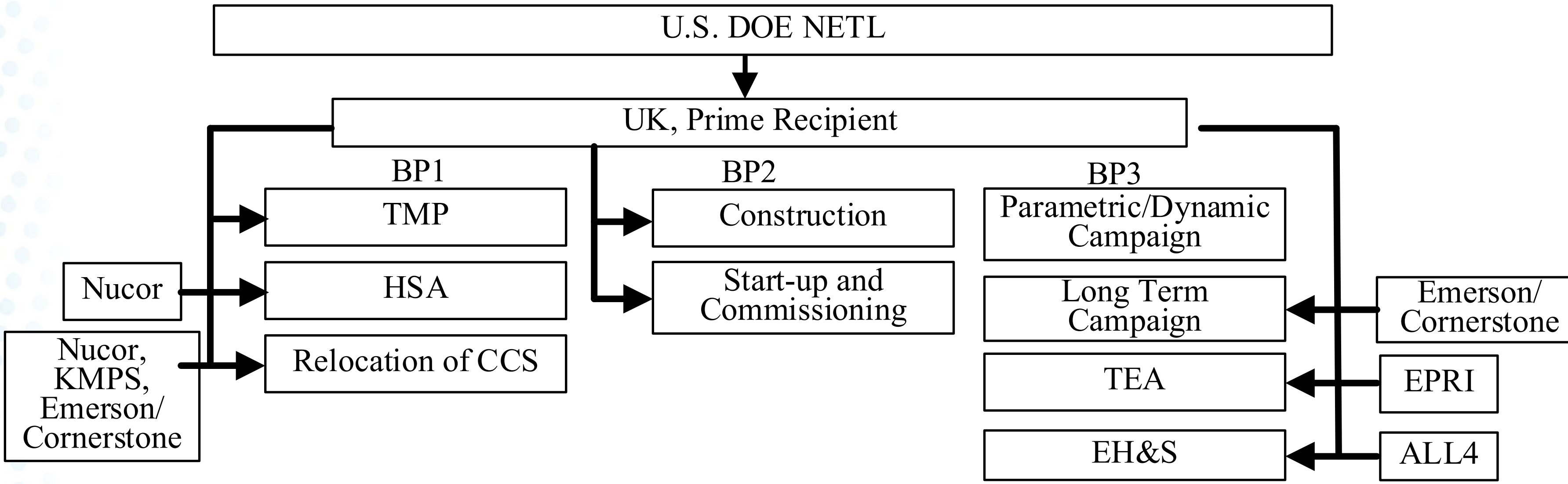
Project Team and Funding



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

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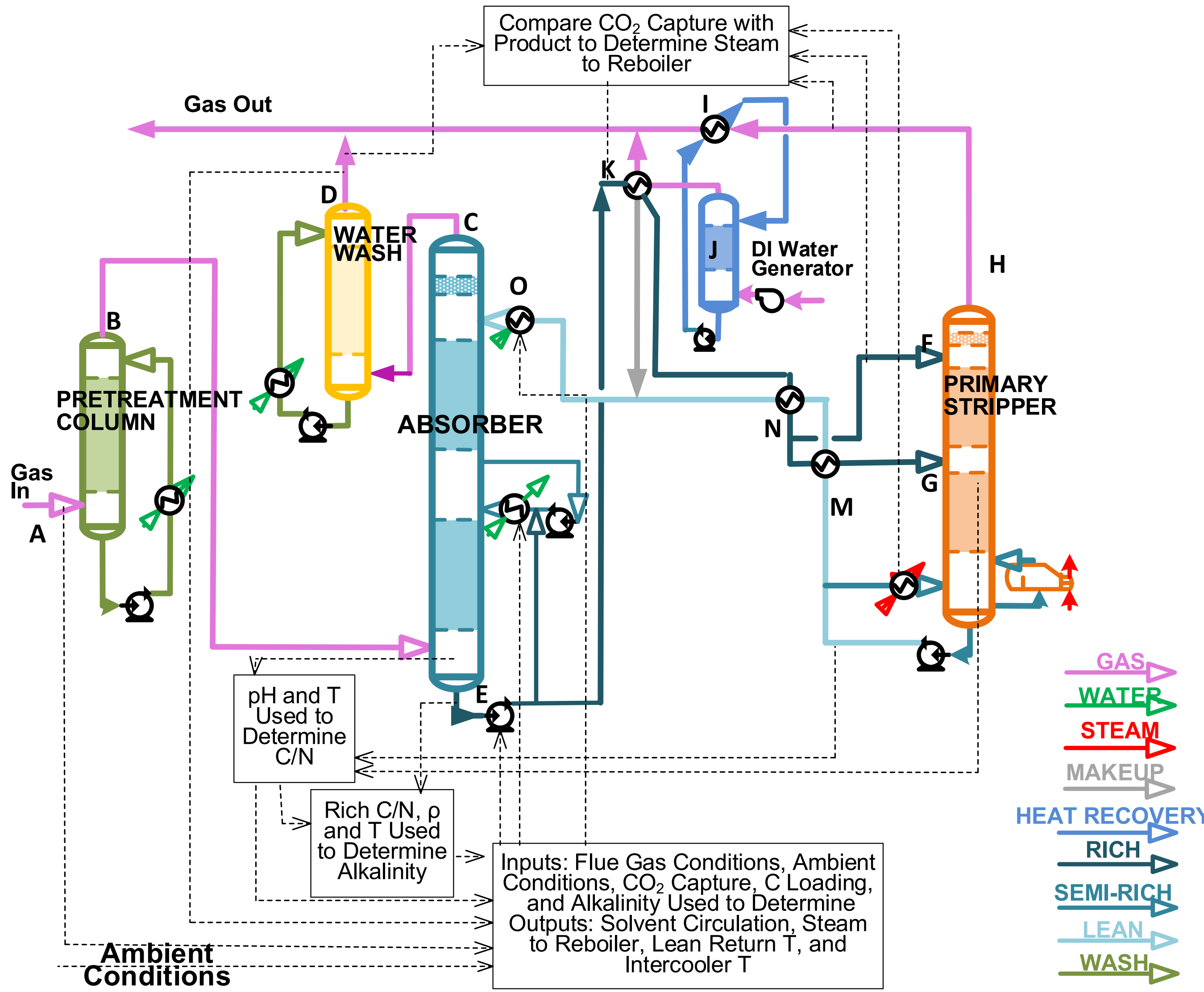
Technology Deployed

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



Technical Approach

- ❑ **Absorber T Profile**
  - ❑ Liquid maldistribution
  - ❑ Bulge T
  - ❑ Mass transfer
  - ❑ ΔP
  - ❑ Solvent cyclic capacity
- ❑ **Split Rich Stripper Feed**
  - ❑ Stripper top to bottom ΔT
  - ❑ Reboiler specific duty
- ❑ **Advanced Process Control Strategy**
  - ❑ Response time
  - ❑ Average performance

Technology Background

UK Field Pilot CO_2 Capture Unit

- ~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 Parametric Campaign → **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

- ~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 Parametric Campaign → **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

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

UK Solvent Parametric Campaign → **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

Technology Background

Technical Advantages

- Simple, solvent-independent 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, poor wettability and less flexible to load changes

Project Challenge

- Repurpose existing equipment with constrained budget

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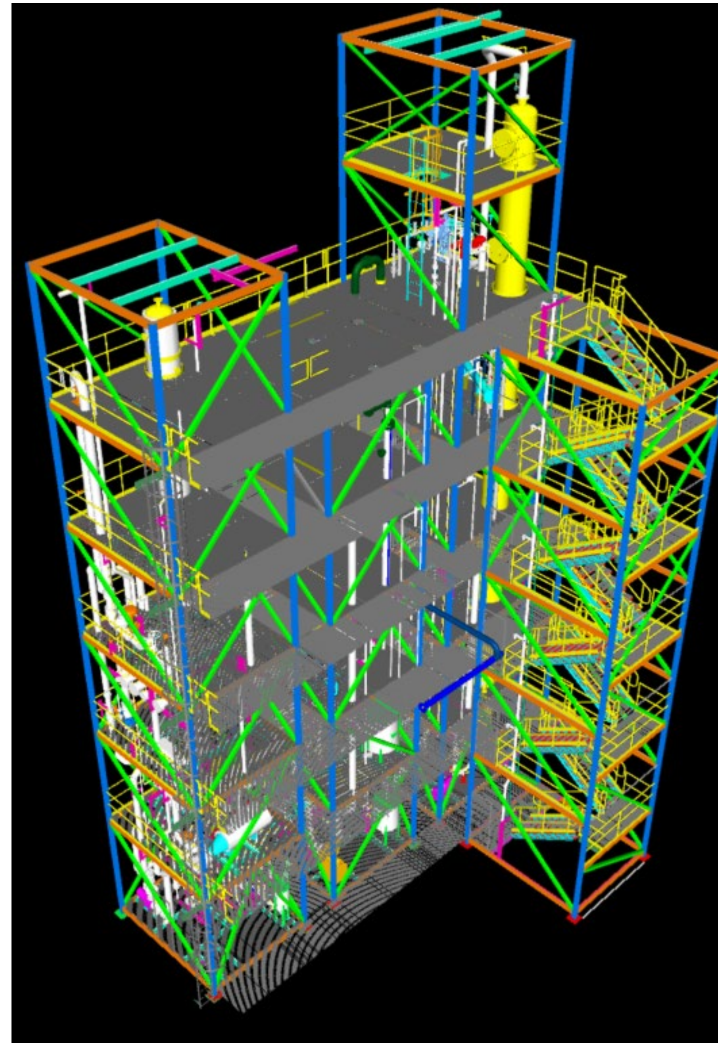
Unit Highlights

- ❑ 3 TPD scale
- ❑ Nucor Steel Gallatin, Ghent, KY
- ❑ 4 repurposed modules
- ❑ Simplified solvent-independent process with cooling tower and steam generator packages
- ❑ UK primary amine solvent applied
- ❑ Installed and tested at on EAF evolved flue gas (0.5-1.5 vol% inlet CO_2 concentrations)
- ❑ Footprint of CCS module: 28 x 44 ft. and 75 ft. tall
- ❑ Construction in 2025, Operation in 2025 and 2026
- ❑ 95+% CO_2 capture efficiency and 99+% CO_2 stream purity
- ❑ Degradation and emission studies
- ❑ Further demonstration of enabling technologies



Read more at:
http://uknow.uky.edu/research/uk-nucor-steel-gallatin-partnering-unique-co2-capture-project?j=492367&sfmc_sub=122676171&l=22565_HTML&u=15148920&mid=10966798&jb=0

Site Selection

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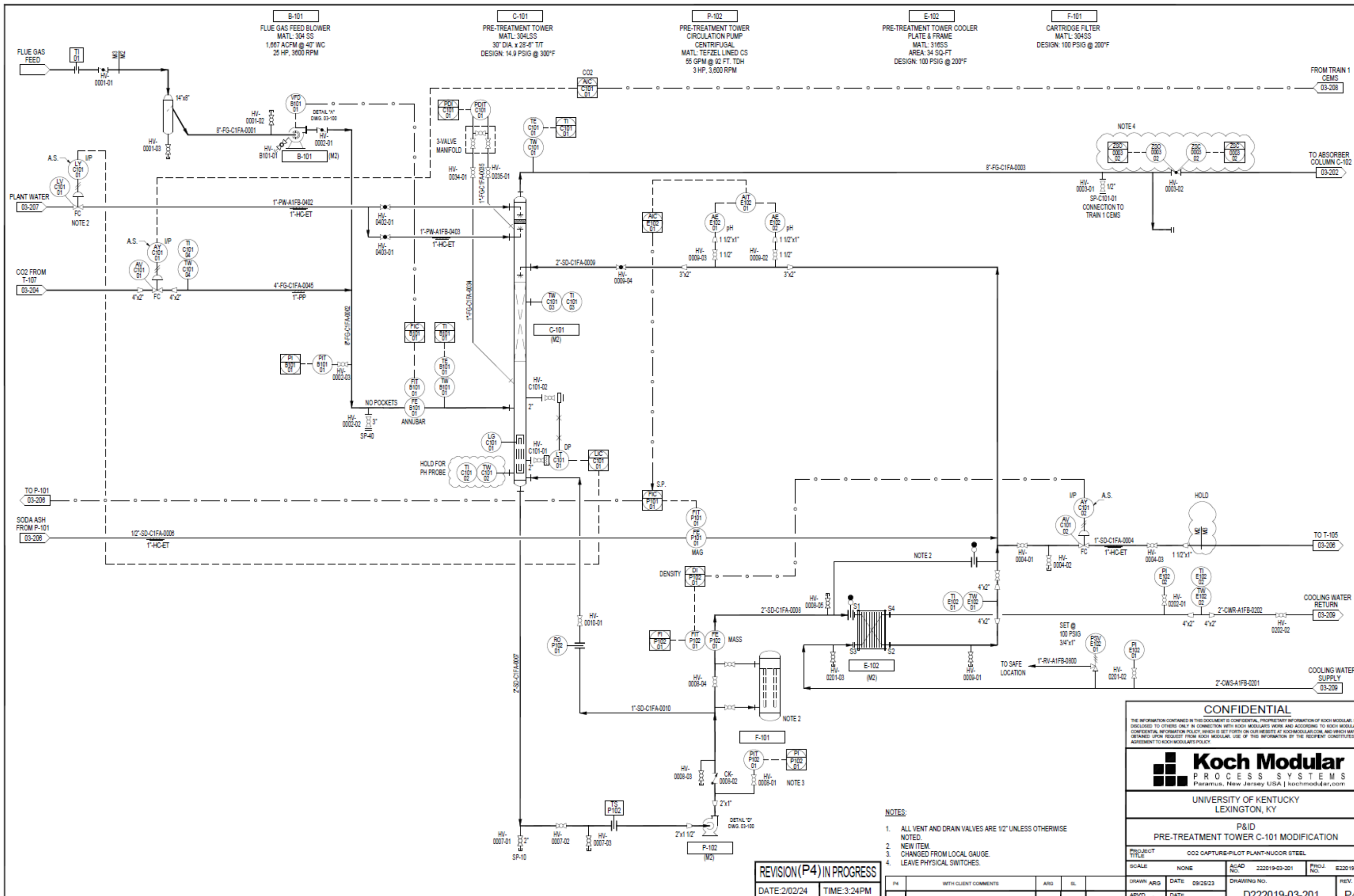
Repurpose Existing Modules with Reconfigurement

✓ ISBL P&IDs - Done

Example: Pretreatment Tower P&ID



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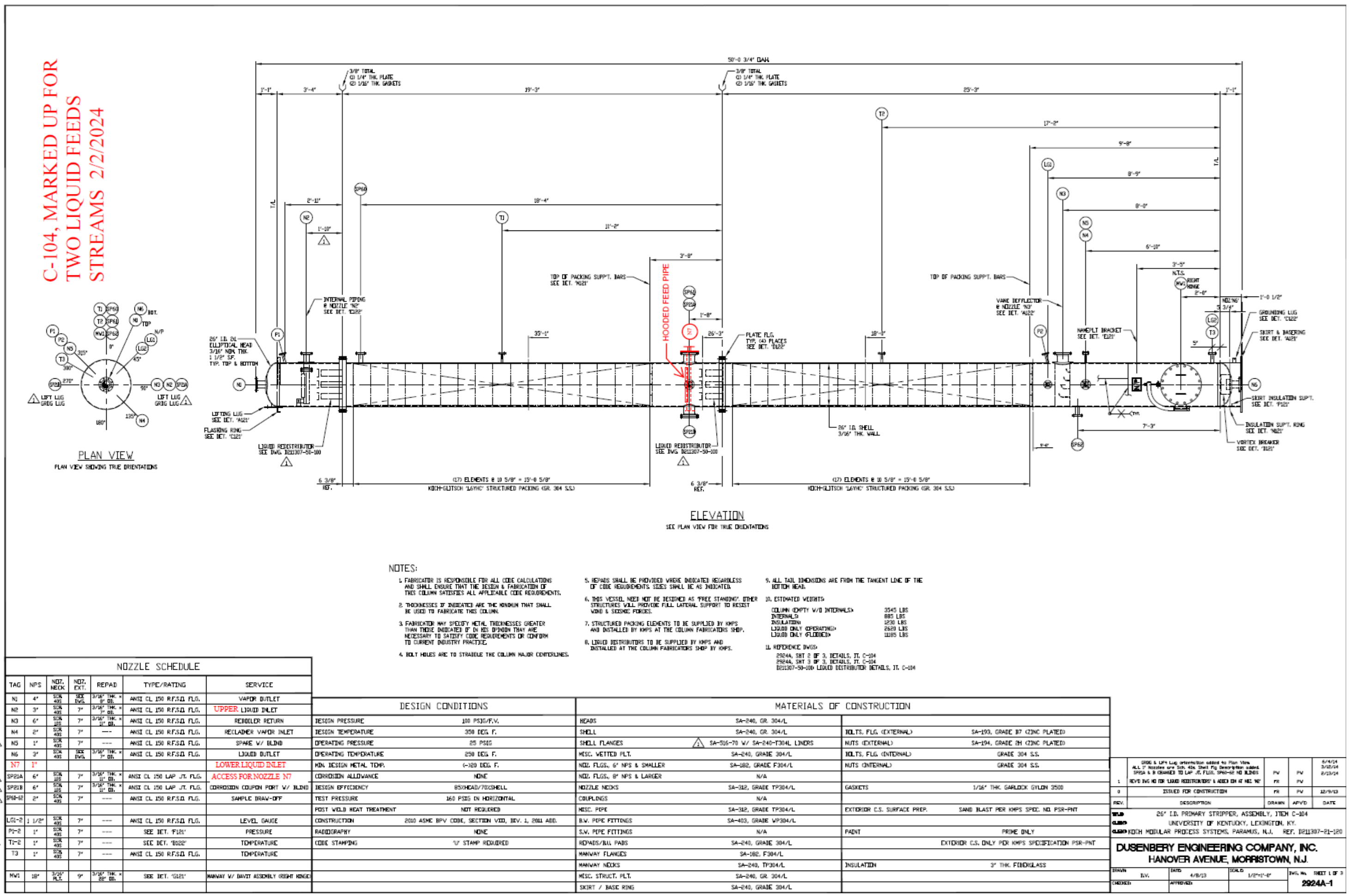
Repurpose Existing Modules with Reconfigurement

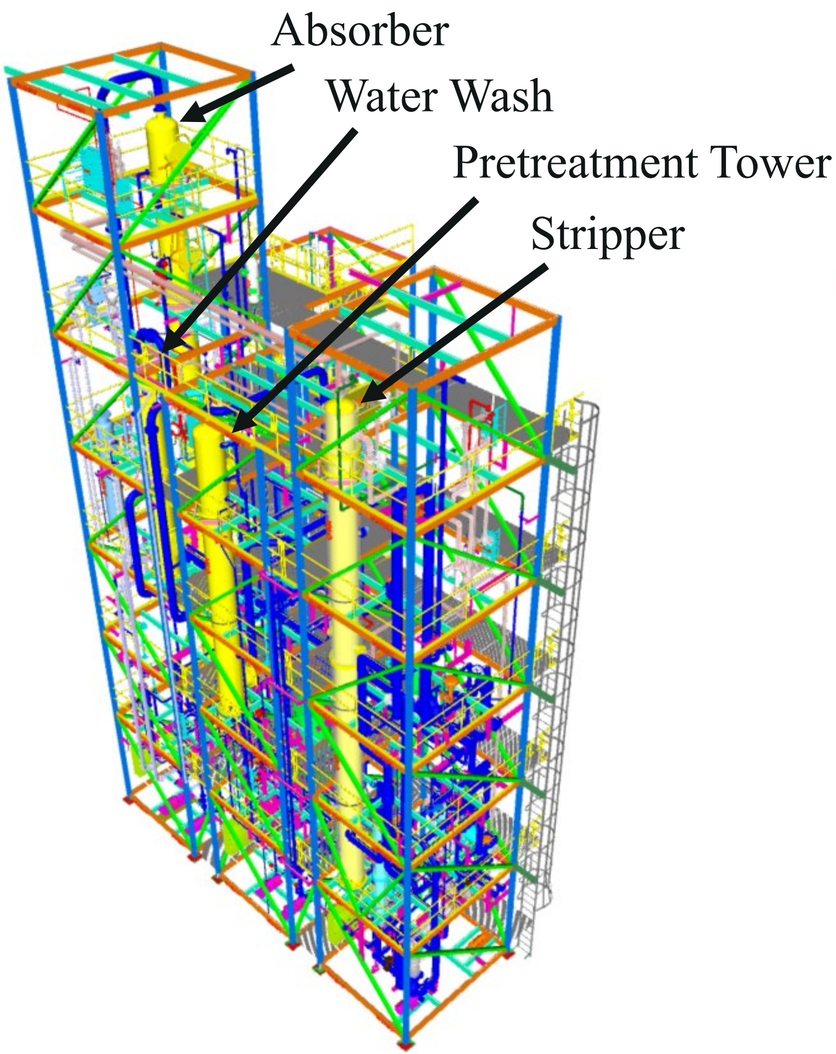
☑ ISBL Existing Equipment Review - Done

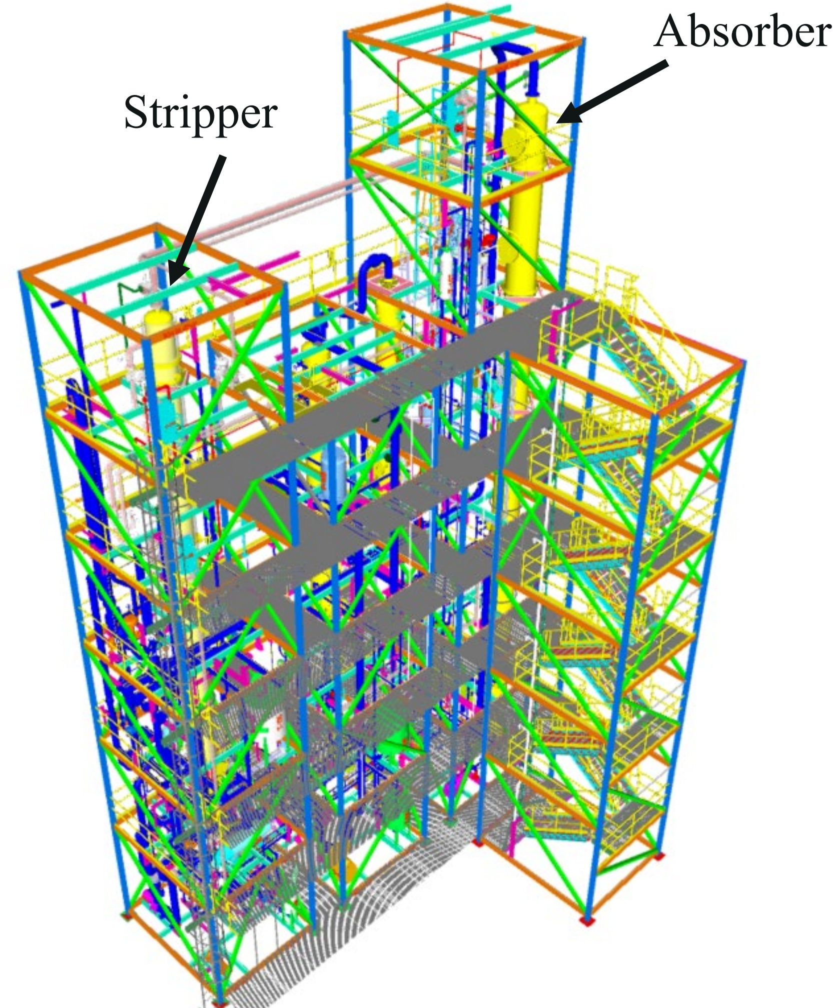
To repurpose existing columns, filters heat exchangers, pumps, the flue gas blower and instrumentation.



Repurpose Existing Modules with Reconfigurement

☑ **ISBL 3-D Model - Done**





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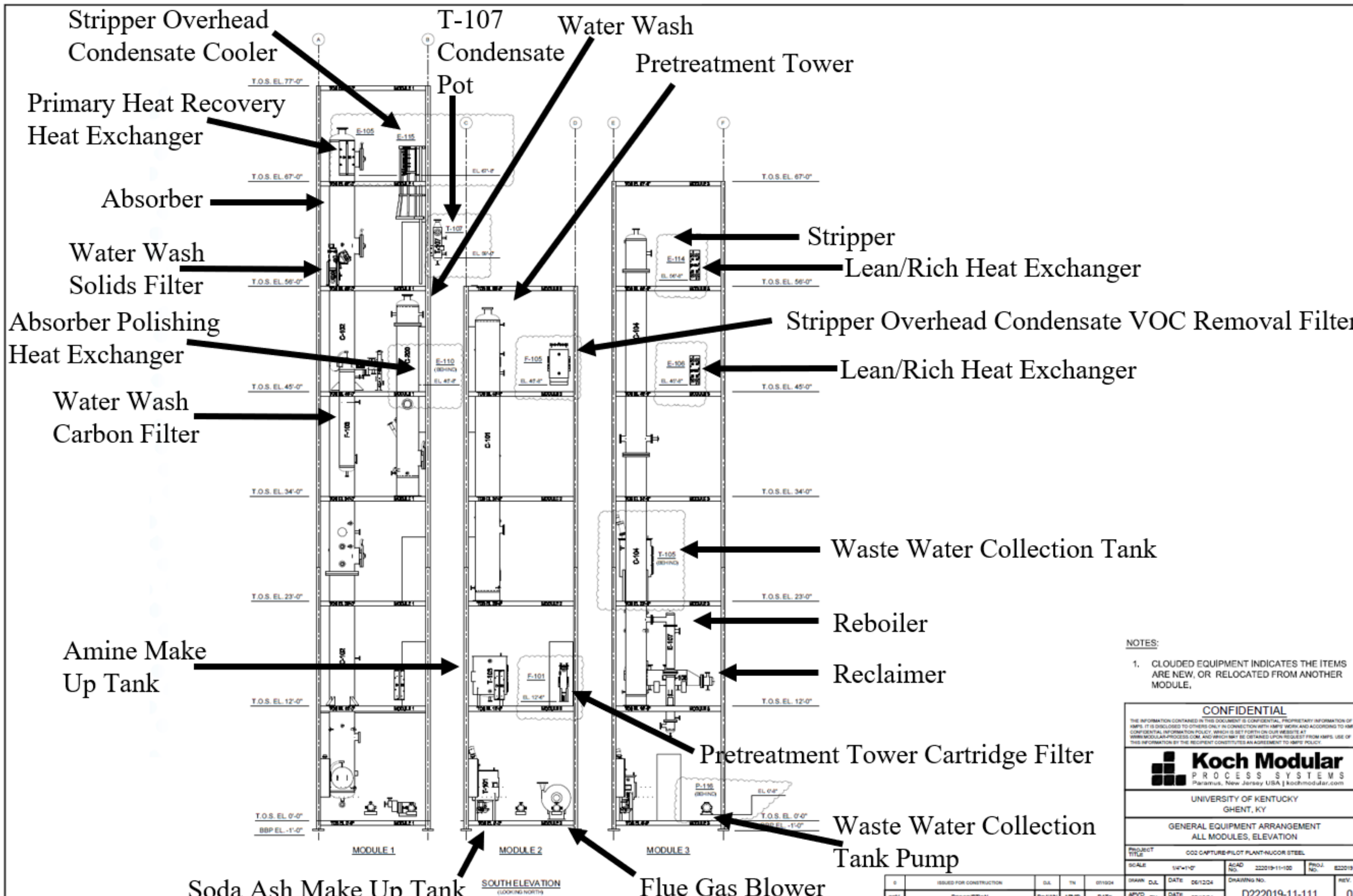
Repurpose Existing Modules with Reconfigurement

☑ ISBL General Arrangement - Done



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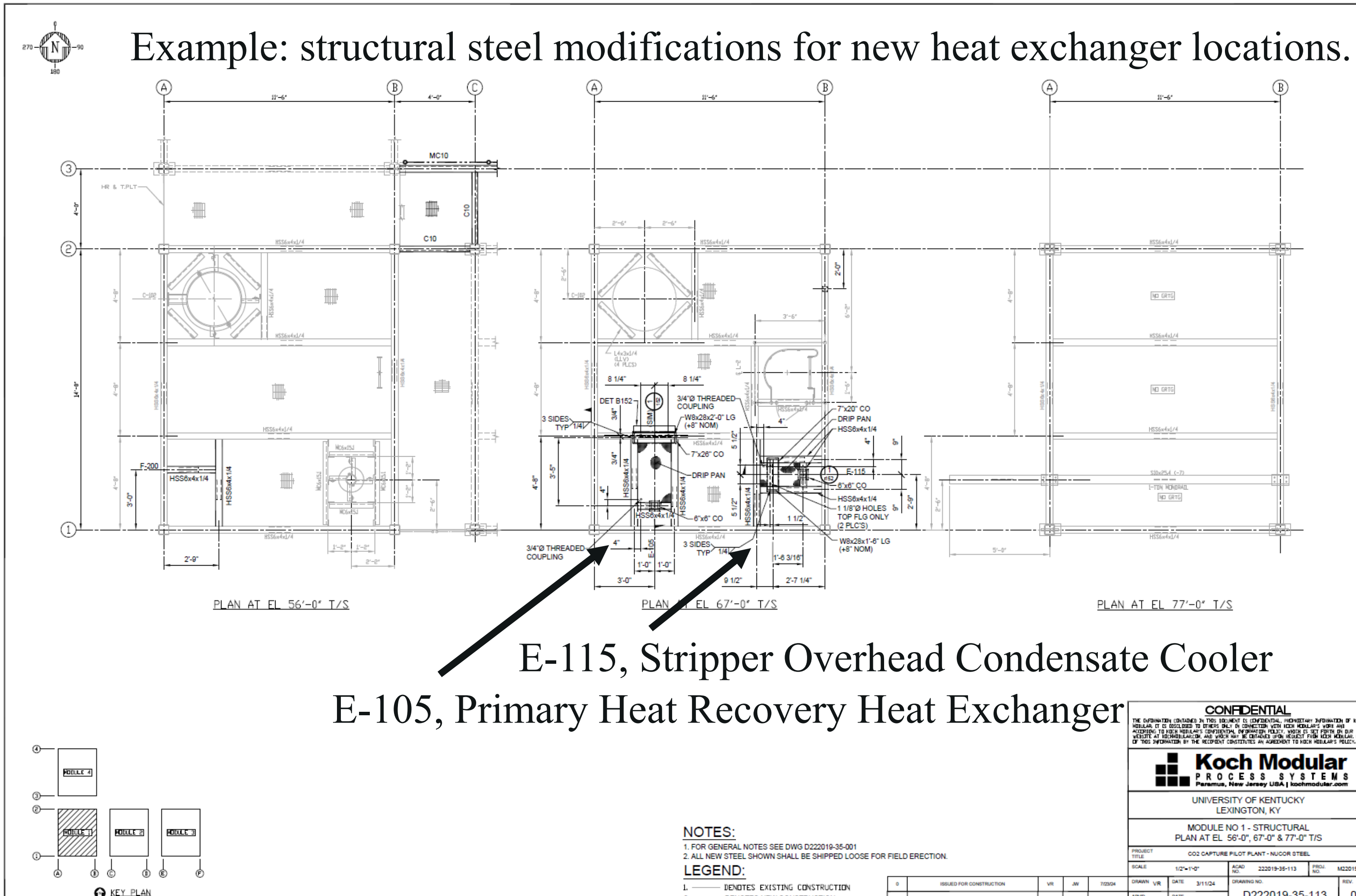
Repurpose Existing Modules with Reconfigurement

☑ **ISBL Structural Steel - Done**



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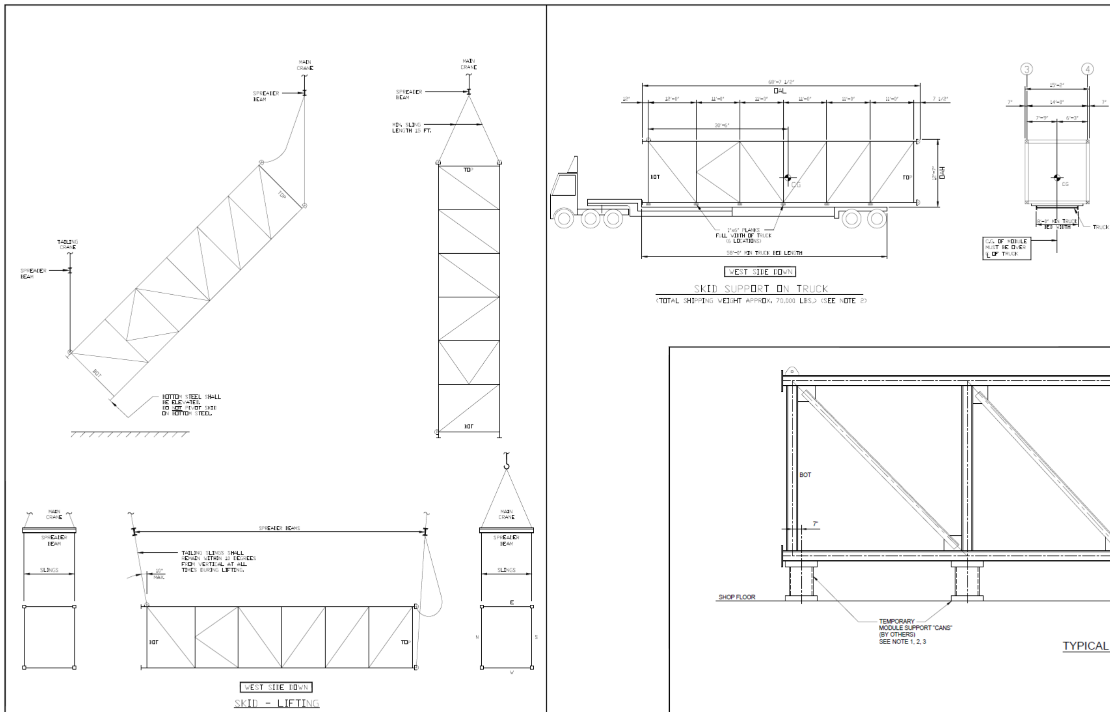
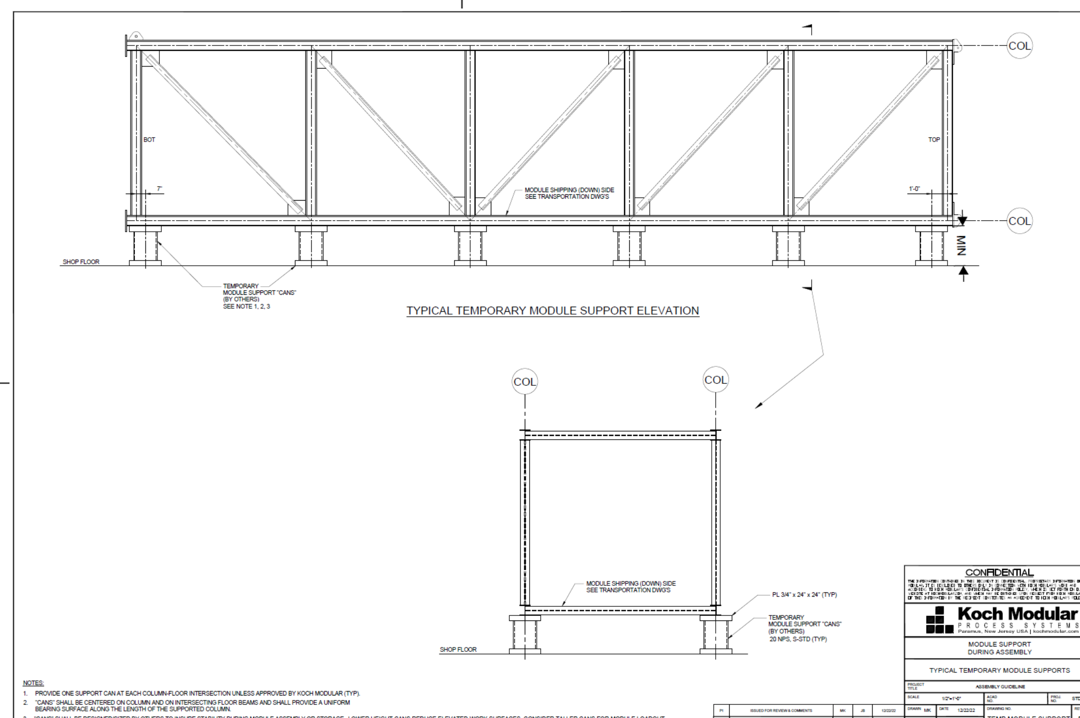
Repurpose Existing Modules with Reconfigurement

☑ **ISBL Module Lifting and Laydown - Done**





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BOP Systems

☑ BOP Systems (CT, Steam Gen, Air Comp) Specification and Competing Quotes Collected - Done

Koch Modular PROCESS SYSTEMS
Paramus, New Jersey - 201.267.8670
kochmodular.com

COOLING WATER RECIRCULATION SYSTEM

Client:	University of Kentucky	Date:	2/6/202
Location:	Ghent, KY (Near Louisville)	Rev:	0
		By:	SYL
		Project #:	E22019
		P&ID:	OSBL EC
		Page:	1 OF 2

GENERAL REQUIREMENTS			
TYPE	INDUCED DRAFT PACKAGED SYST.	INSTALLATION	OUTDOOR
SERVICE	CHEMICAL INDUSTRY	SUPPLIER/MODEL	
OPERATING CONDITIONS		**CONSTRUCTION**	
HEAT TRANSFER FLUID	WATER	SHELL	HDPE OR FRP
TOTAL FLOW (GPM)	35	FILL	PVC
TOTAL FLOW, MAX (GPM)	50	MIST ELIMINATOR	Vendor to advi
		FAN	FRP BLADES
TOTAL DUTY (BTU)	183,000		
TOTA DUTY, MAX (BTU)	250,000	CIRCULATION PUMP-TYPE	CENTRIFUGAL
TOTAL DUTY, MIN (BTU)		WETTED PARTS	CS OR DUCTILE IF
		CASING	CS OR DUCTILE IF
TEMPERATURE, SUPPLY (F)	85		
TEMPERATURE, RETURN (F)	100	MANUFACTURER/MODEL OR EQUAL	Cooling Tower Systen
REQUIRED PUMP HEAD (FT)	120	https://www.coolingtowersystems.com/collections/model-t-2/products/model-t-240	
ELECTRICAL REQUIREMENTS			
MOTORS		TEFC	
ENCLOSURE FOR CONTROLS		NEMA 4X(FIBERGLASS/AIR PURGED) OR PAINTED SS	
MOTOR STARTER ENCLOSURES		GENERAL PURPOSE	
PH/Hz/V		3/60/460	
SERVICE FACTOR		1.15	
MOTOR CLASSIFICATION		GENERAL PURPOSE	
AREA CLASSIFICATION		GENERAL PURPOSE	
CIVIL & STRUCTURAL REQUIREMENTS			
INSTALLATION		OUTDOOR	
NOISE LEVEL		<80 dB	
WIND DESIGN CRITERIA			
RISK CATEGORY		II	
BASIC WIND SPEED		115 MPH	
SEISMIC DESIGN CRITERIA			
RISK CATEGORY	II	IMPORTANCE FACTOR I_e	1
SITE CLASS	D	SEISMIC DESIGN CATEGORY	C
S_S	0.157	R	3.5
S_1	0.086		
TEMPERATURE DESIGN CRITERIA			
WET BULB TEMPERATURE		79 °F (NOTE 2)	

NOTES

1. SELLER MAY RECOMMEND ALTERNATIVE MATERIALS IF COMPATIBLE WITH THE PROCESS
2. VENDOR TO CONFRIRM THAT THE 120 FT OF TDH CAN BE MET.
3. SEE PAGE TWO FOR MORE DETAILED DESIGN CRITERIA TEMPERATURES FOR LOUISVILLE, KY

Cooling Tower

Brand	Lead Time	Cost
A	3-4 weeks after receipt of purchase order	$6,008.40
		-
		$6,008.40
B	TBD	$7,000.00
		$840.00
		$2,388.00
		$165.00
		$12,781
C	14-18 weeks	$17,025
		$1,452
		$18,477

Decommissioning

- ☑ **Decommissioning SOW started**
  - ❑ Solvent removed and prepared for shipping
  - ❑ Amine loop, addition lines and tanks rinsed
  - ❑ Water wash tank cleaned
  - ❑ AC removed and bed rinsed
  - ❑ Temporary insulation removed
  - ❑ CEMS disconnected and sample lines removed

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Experimental Plan

- **Parametric Campaign**
  - ~5 months
- **Dynamic Testing with/out Feed-Forward Process Control**
  - ~1 month
  - CO_2 capture efficiency
- **Long-Term Campaign**
  - ~3 months, continuous operation included

- Measure: CO_2 capture efficiency, energy consumption, flue gas ΔP, absorber CO_2 mass transfer flux, attainable rich carbon loading, stripper top to bottom ΔT, reboiler specific duty, ramp rate and operability to achieve 95+% capture including ambient conditions and external load changes
- Vary: inlet CO_2 concentration, lean solvent flow rate, flue gas flow rate and T, lean solvent physical properties, inter-stage cooling duty, stripper P, reboiler T, absorber T profile

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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	11/30/2024	
1	Boiler Procurement Decision Point Meeting	8/31/2023	8/23/2023
1	General Contractor Selected	11/30/2024	
2	Nucor Site Prepared for Installation	4/3/2025	
2	CCS Installed at Nucor	8/1/2025	
2	Test Plan Complete	8/1/2025	
2	Commissioning Complete	11/30/2025	
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)	3/31/2026	
3	Long-term Campaign Complete (1000 hours showing optimized process conditions, dynamic stability and operability)	6/30/2026	
3	TEA Complete	8/31/2026	
3	EH&S Complete	8/31/2026	

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

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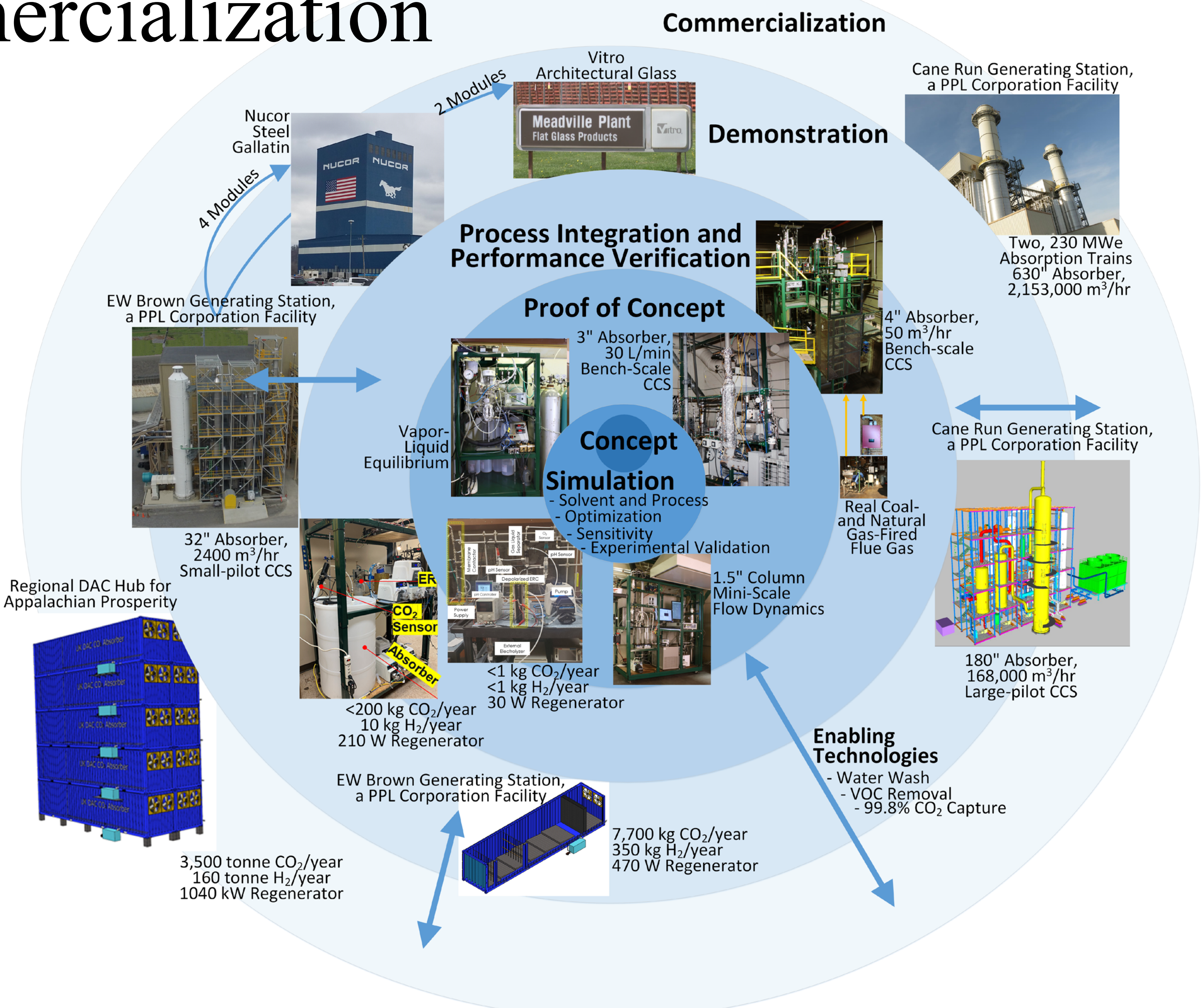
Current Status

1. Host Site Agreement Executed
2. KMPS to be complete with ISBL design by end of August.
3. Nucor to complete BOP engineering and installation.

Collaboration with CCSI^2

1. Design of experiments to minimize system performance uncertainty using limited experimental runs
2. Understand system performance impact from internal and external disturbances such as control valves and ambient conditions
3. Study the overall performance under dynamic operation
4. Investigate packing behavior such as wettability, channel flow and liquid hold up under dynamic operation
5. Develop a Fortran plug-in to estimate the wettability and mass transfer coefficient from gas velocity, liquid loading, local temperature and solvent chemical composition

Future Development & Commercialization



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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

Acknowledgements

U.S. DOE NETL: Krista Hill and Dan Hancu

Nucor Steel Gallatin: Rob Rosenbaum, Paul Shovlin, Anna Mauser, and Hunter Summers

EPRI: Abhoyjit Bhown

Emerson/Cornerstone: Vigen Biglari

ALL4: Karen Thompson

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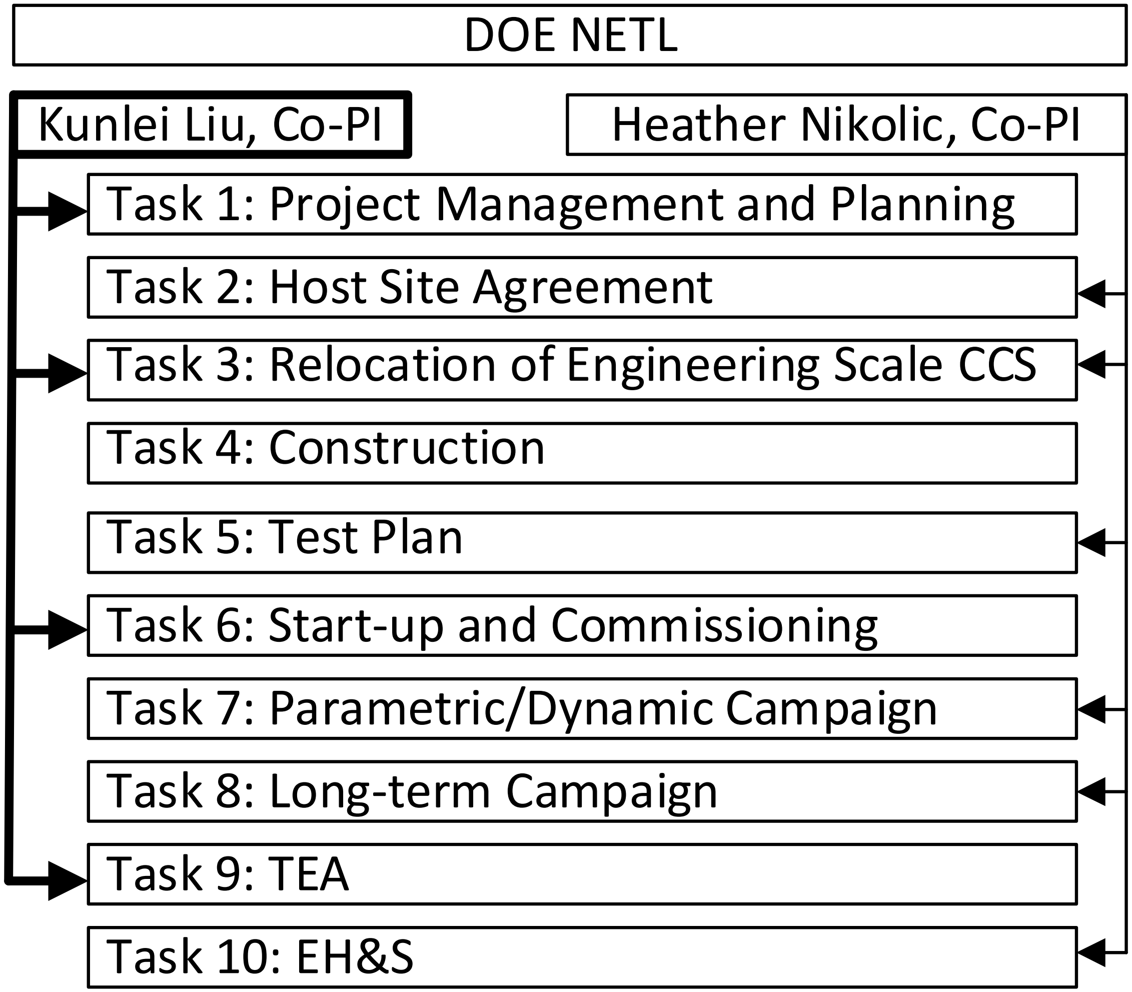
Targets for Cost Reduction

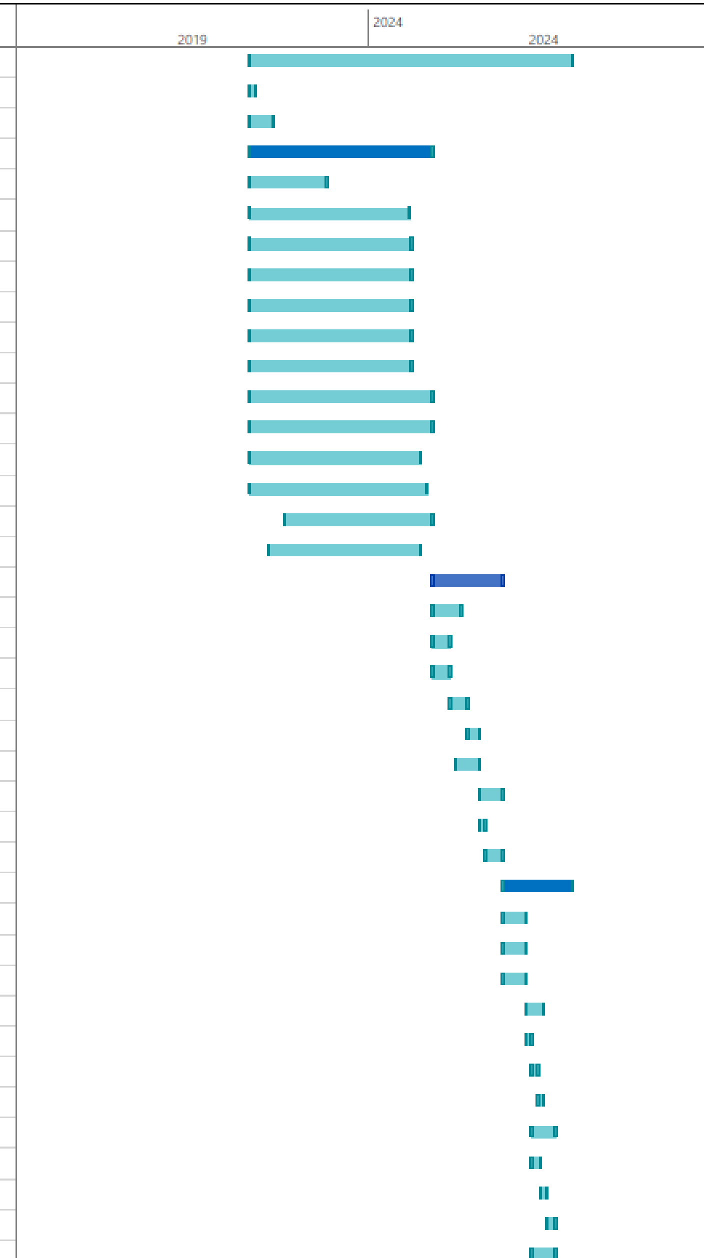
	B31A	B31B	UK Process
Capture Efficiency, %	N/A	90	95.0
Total Plant Cost, $/1000	566971	1281324	972500
Net Power Output at Design Condiiton, MMe	727	646	647
COE ($/MWh)	**43.3**	**70.8**	**61.5**
Fuel Costs	28.1	31.6	31.5
Variable Costs	1.7	5.6	4.4
Fixed Costs	3.6	8.6	6.6
Capital Costs	9.9	25.0	18.9
CO_2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

ID	Task Name	Start	Finish
1	1. Project Management and Planning	Mon 4/25/22	Mon 11/30/26
2	1.1. PMP	Mon 4/25/22	Tue 5/24/22
3	1.2. TMP	Mon 4/25/22	Wed 8/24/22
4	**Budget Period 1**	**Mon 4/25/22**	**Sat 11/30/24**
5	2. HSA	Mon 4/25/22	Wed 5/31/23
6	3. Relocation of Engineering Scale CCS	Mon 4/25/22	Wed 7/31/24
7	3.1. Reconfiguration	Mon 4/25/22	Thu 8/15/24
8	3.1.1. Absorber Internals	Mon 4/25/22	Thu 8/15/24
9	3.1.2. Split Rich Stripper Feed	Mon 4/25/22	Thu 8/15/24
10	3.1.3. Advanced Control Strategy	Mon 4/25/22	Thu 8/15/24
11	3.1.4. Process Simplification	Mon 4/25/22	Thu 8/15/24
12	3.2. Boiler	Mon 4/25/22	Sat 11/30/24
13	3.3. Site Survey and Preparation	Mon 4/25/22	Sat 11/30/24
14	3.4. Deconstruction and Removal Planning	Mon 4/25/22	Mon 9/30/24
15	3.5. Shipping Preparation	Mon 4/25/22	Thu 10/31/24
16	3.6. General Contractor Selection	Tue 10/25/22	Sat 11/30/24
17	3.7. HAZOP Evaluation	Mon 8/1/22	Mon 9/30/24
18	**Budget Period 2**	**Sun 12/1/24**	**Sun 11/30/25**
19	4. Construction	Sun 12/1/24	Wed 4/30/25
20	4.1. Foundation	Sun 12/1/24	Fri 2/28/25
21	4.2. Decommissioning and Shipping	Sun 12/1/24	Fri 2/28/25
22	4.3. Installation	Sat 3/1/25	Sat 5/31/25
23	4.4. Tie-ins	Sun 6/1/25	Thu 7/31/25
24	5. Test Plan	Tue 4/1/25	Thu 7/31/25
25	6. Start-up and Commissioning	Fri 8/1/25	Sun 11/30/25
26	6.1. Commissioning Plan	Fri 8/1/25	Sun 8/31/25
27	6.2 Start-up and Commissioning	Mon 9/1/25	Sun 11/30/25
28	**Budget Period 3**	**Mon 12/1/25**	**Mon 11/30/26**
29	7. Parametric/Dynamic Campaign	Mon 12/1/25	Tue 3/31/26
30	7.1. Absorber Packing Performance	Mon 12/1/25	Tue 3/31/26
31	7.2. Reboiler Specific Duty	Mon 12/1/25	Tue 3/31/26
32	8. Long-term Campaign	Wed 4/1/26	Tue 6/30/26
33	8.1. System Dynamic Stability and Operability	Wed 4/1/26	Thu 4/30/26
34	8.2. Reboiler Specific Duty Minimization	Fri 5/1/26	Sun 5/31/26
35	8.3. Packing Operability under Cyclic Operating Environment	Mon 6/1/26	Tue 6/30/26
36	9. TEA	Fri 5/1/26	Mon 8/31/26
37	9.1. Modeling	Fri 5/1/26	Mon 6/15/26
38	9.2. Equipment Sizing	Tue 6/16/26	Wed 7/15/26
39	9.3. Analysis	Thu 7/16/26	Mon 8/31/26
40	10. EH&S Risk Assessment	Fri 5/1/26	Mon 8/31/26



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