Engineering-scale test of a water-lean solvent for post-combustion capture

DE-FE0031945

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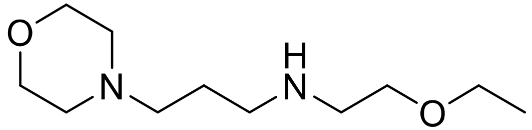
Project Overview

			Modified dates & budget, pending approval
DOE PM	Dustin Brown		
Project period	October 2020 to March 2024		*to June 2025*
Funding	Federal	$4,129,607	*$5,028,677*
	Cost share	$1,032,411	*$1,257,169*
	Total	$5,162,018	*$6,285,846*
Organizations	Electric Power Research Institute Pacific Northwest National Lab. RTI International Paul M. Mathias Consulting, LLC Gradient Worley Southern Company Services (NCCC)		

Objective – Perform extended test campaigns on coal and natural gas flue gases with the EEMPA solvent operating at the ~0.5 MWe-equivalent scale for both coal and gas to verify its favorable performance characteristics while evaluating the environmental, health and safety (EH&S) risks of the technology and quantifying its potential to lower the cost of CO_2 capture.



N-(2-ethoxyethyl)-3-morpholinopropan-1-amine

or

EEMPA

Overview of EEMPA's characteristics

Strengths

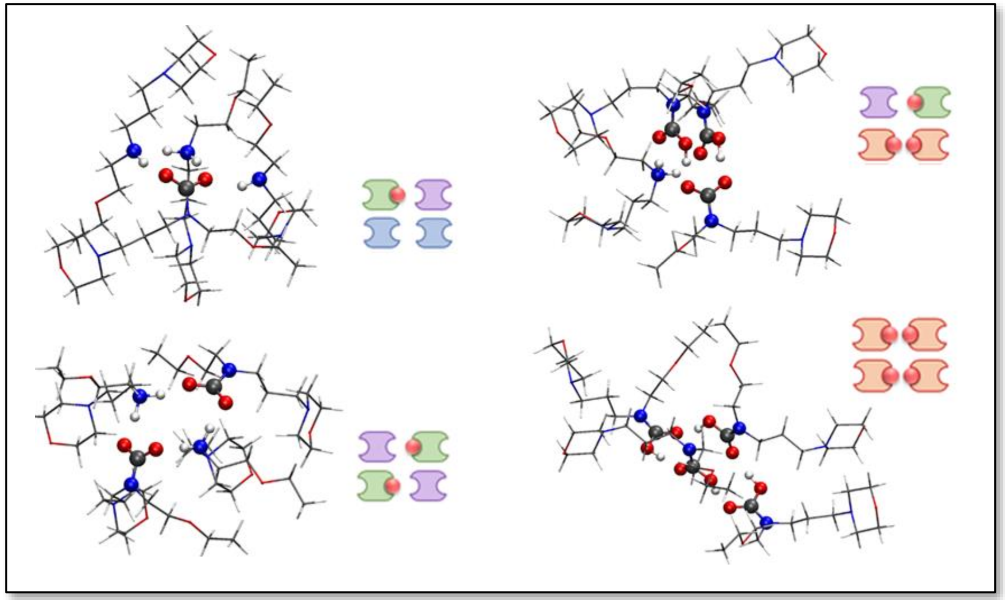
- Single-component, miscible in water
- Low viscosity gain upon reaction with CO_2
- Low surface tension
- Compatible with potentially cheaper materials of construction (e.g., plastics)
- Low corrosivity
- Good thermal and chemical stability
- Potential for advanced heat integration and regeneration steps that could save costs (e.g., flash regeneration)

Challenges

- Solvent is presently costly to produce, and large-scale production yet to be demonstrated
- Imposes need for careful control of the process water balance

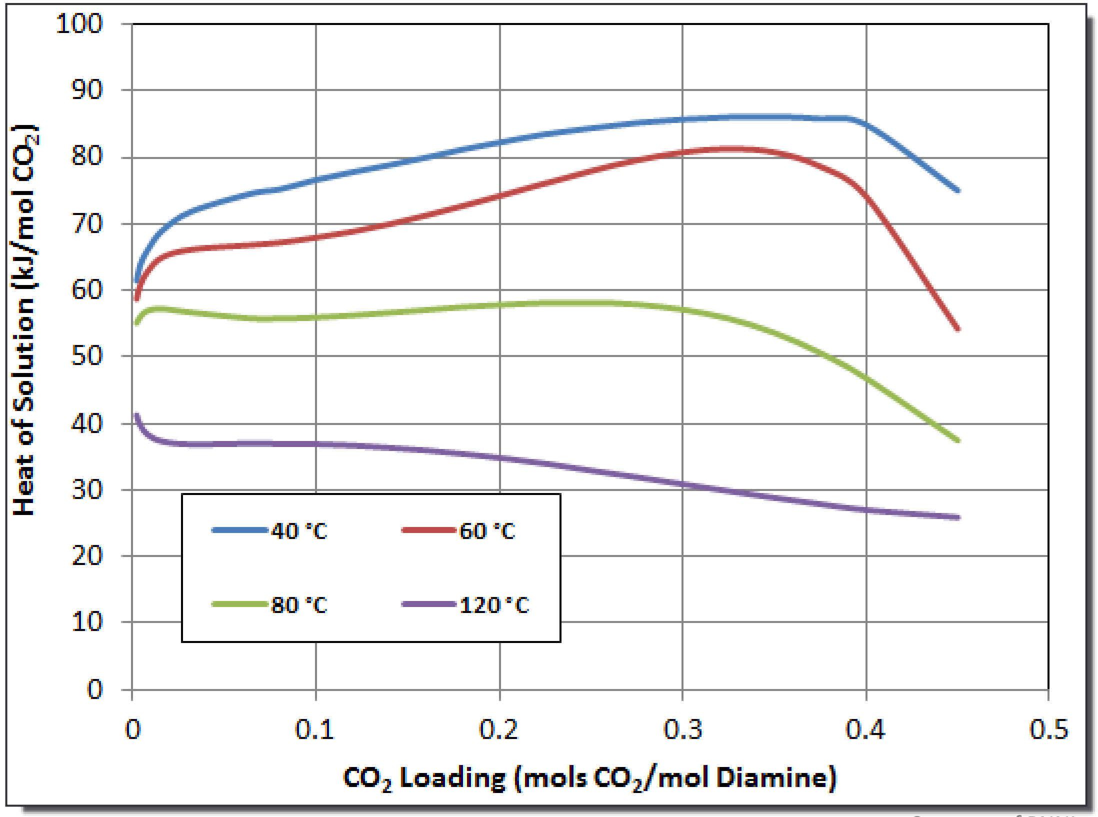
EEMPA has several characteristics that make it a promising post-combustion capture solvent

EEMPA's chemistry helps lead to the potential for low specific reboiler duties



Courtesy of PNNL

- Spectroscopic and computational evidence point to enthalpically favored formation of EEMPA tetramers.
- *Current hypothesis*: denaturing of these tetramers leads to observed changes in heat of solution.[1]
- SRDs as low as 2.0 GJ/t CO_2 have been observed in lab experiments.[2] Cost-optimal designs for coal flue gas achieve 2.34 GJ/t CO_2 captured.[3]



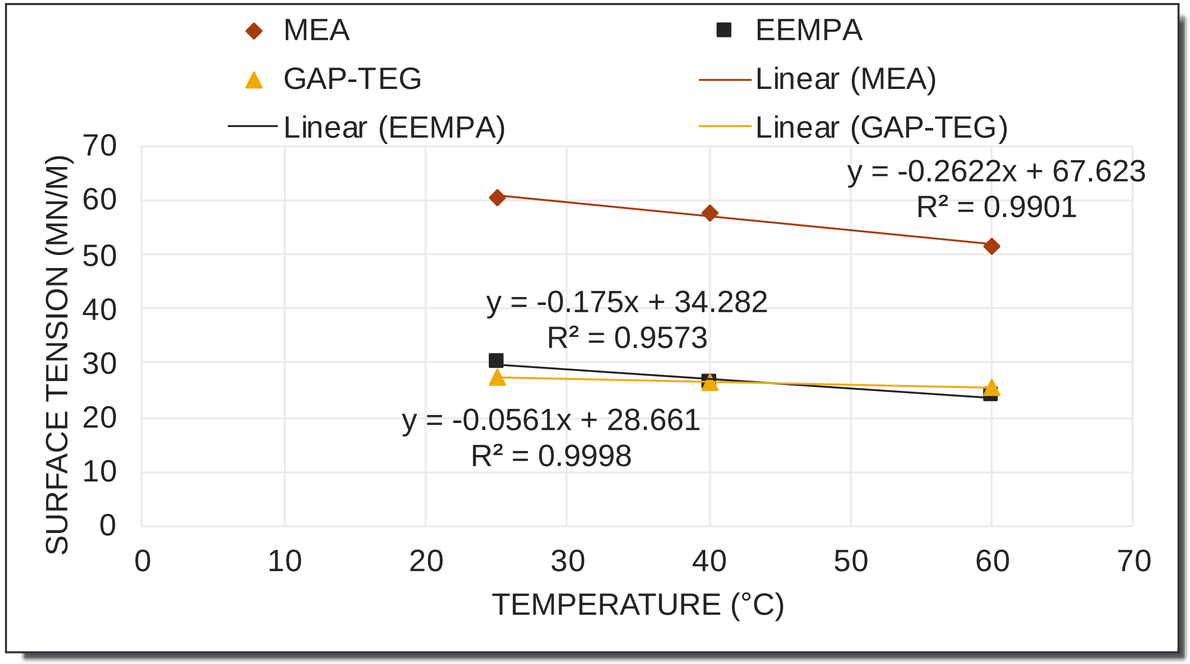
Courtesy of PNNL

This figure shows the heat of solution of CO_2 absorbing into dry EEMPA as a function of loading and temperature. At fixed loading, the heat of solution decreases with increasing temperature.

1. Heldebrant et al. (2023), *In review.*
2. Zheng et al., *Energy. Environ. Sci.* (2020), *13*, 4106-4113.
3. Jiang et al., *IJGHGC*, (2021), *106*, 103279.

EEMPA may capture benefits from the use of plastics

- EEMPA is chemically compatible with a range of polymer materials, including polyolefins like polypropylene
- EEMPA exhibits a low surface tension (see right) an ability to wet many of these materials
- Potential benefits include…
  - Capital cost savings through cheaper absorber packing
  - Lower degradation rates by eliminating a source of metal ions that might catalyze particular degradation pathways
  - Enhancement of mass transfer characteristics through favorable solvent-packing interaction



Courtesy of PNNL

Plot of observed surface tension vs. temperature for EEMPA and other solvents. EEMPA exhibits a significantly lower surface tension than monoethanolamine.

Grubel et al. *In preparation.*

Scope for an engineering-scale test

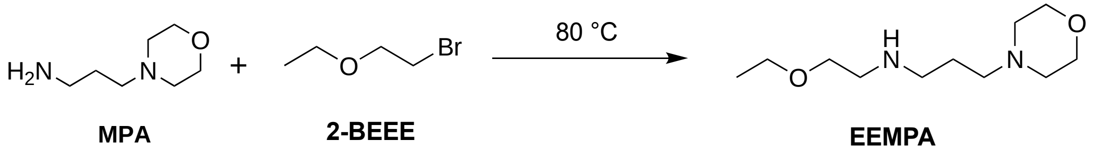
- Develop a route to produce larger volumes of EEMPA at lower cost
- Plan a test using the Pilot Solvent Test Unit (PSTU) at the National Carbon Capture Center
- Modify PSTU equipment to accommodate EEMPA
- Manufacture the required quantity of solvent
- Run test campaigns on coal and natural gas flue gases
- Conduct a final TEA and environmental, health, and safety (EH&S) risk assessment

Image courtesy of Southern Company Services

Establishing alternatives for synthesizing EEMPA

Objectives

- Develop alternatives to the single-step established route, which reacts 4-morpholinopropyl amine (MPA) with 2-bromoethyl ethyl ether (2-BEEE) to yield EEPMA.

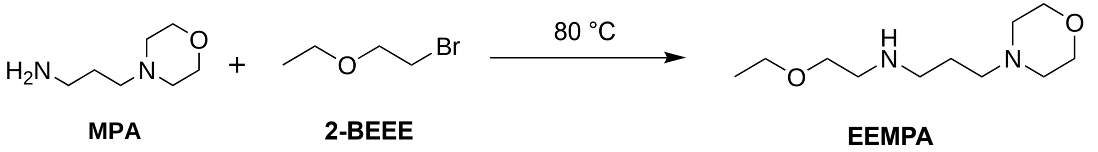
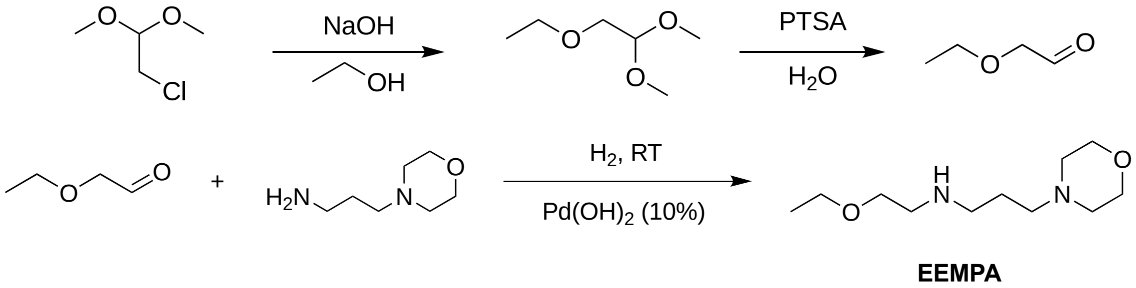
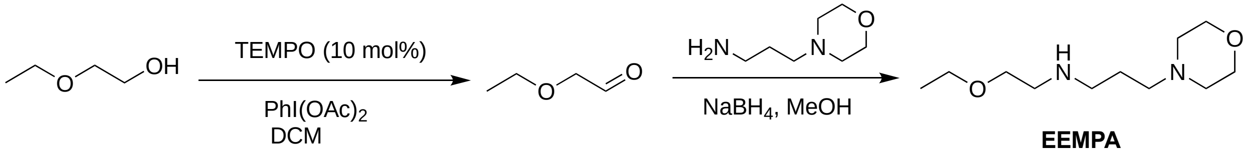
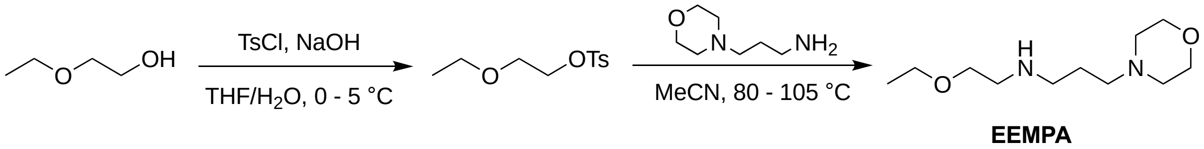


- 2-BEEE must be shipped under refrigeration, adding substantially to its procurement cost and logistics.
- Evaluate the most promising alternatives for the potential to achieve a $10/kg cost target.

Outcomes

- Several promising alternatives were identified using less expensive, widely available feedstocks.
- At present pricing for the scale required for this project (7.5 t), further development is required to translate the best alternatives to larger scales and achieve potential cost reductions.

Highest readiness synthesis routes considered

Route No.	AKA	Reactions	Remarks
0	2-BEEE route Established route		• Established procedure with high yield (80%) that has been to used to produce several multi-liter batches • One-step process • Relies on expensive 2-BEEE
1	Chlorodiacetal route		• Uses inexpensive starting materials. • High yield of aldehyde intermediate • Overall yield closer to 50%. Multiple strategies were unable to increase the yield • Multi-step process with intermediate purifications required.
2	2-ethoxyethanol oxidation route		• Widely available feedstock • Potential for a one-pot synthesis • Very high yield of the aldehyde • Inconsistent yields of EEMPA observed
3	Tosylated ether route		• Widely available, low-cost feedstock • Moderate to high yields observed • Requires intermediate purification

Setup process for larger-scale synthesis

Objectives

- Test larger batches of most promising routes to confirm yields
- Determine feedstock availability and pricing at toll manufacturing scale
- Identify toll manufacturers and evaluate quotes for manufacturing 7.5 t (about 2,000 gallons) of EEMPA.

Outcomes

- We solicited quotes from multiple toll manufacturers. Due to extra steps and lower level of development, the best alternative was quoted at higher cost than the original route.
- 2-BEEE has become ~3 times more expensive than during the proposal phase.
- The team has selected a manufacturer and quote based on the established route.

Planning for NCCC testing development

- Developed Aspen Plus models for coal and NGCC-like flue gas scenarios for the PSTU with the EEMPA property models

- An initial evaluation of the cooling needs to achieve the desired water balance in PSTU was performed (see right).

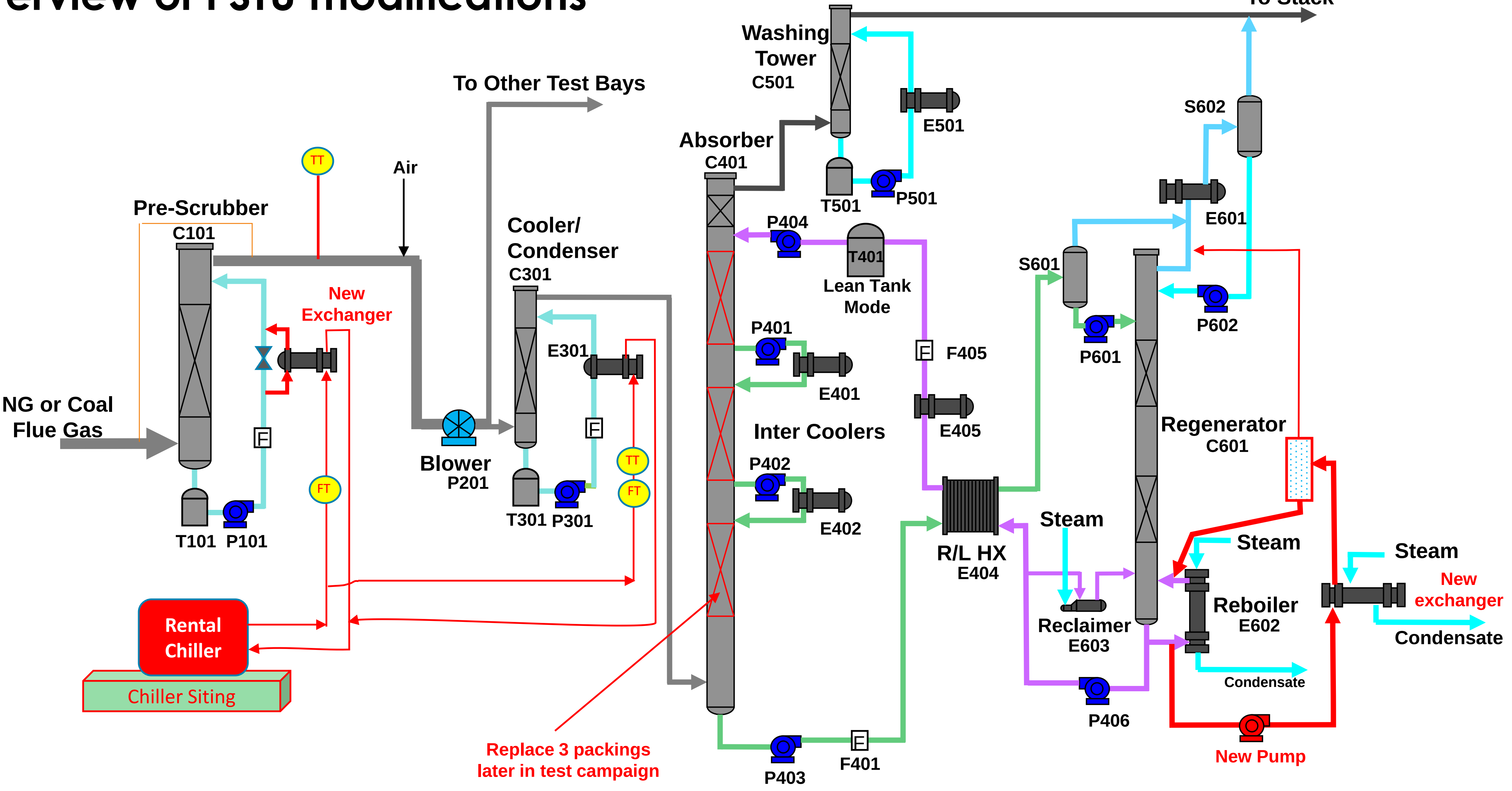
Modeled cooling duties required to achieve target dew points for natural gas and coal conditions

		NGCC conditions	Coal conditions
Starting temperature range	°F	110-130	110-180
Target absorber inlet temperature	°F	68.0	60.5
Total duty	Btu/hr	148,800-158,400	339,600-373,200
	tons of refrigeration	12.4-13.2	28.3-31.1

Equipment engineering and cost

- Further evaluation helped determine two key areas for modification of the PSTU to achieve target performance:
  - Enhancing cooling of the flue gas using both the pre-scrubber and cooler/condenser column
  - Using a larger reboiler to supply sufficient heat transfer area for the needed duty.
- Cooling the flue gas
  - New exchanger will be added to cool the pre-scrubber
  - Chilled water will be provided to both this exchanger and the existing cooler/condenser exchanger.
- Reboiler enhancement
  - A new steam heater will be installed along with a forced circulation pump to provide the required heating duty.
  - A larger exchanger is required compared to the existing reboiler due to lower thermal conductivity of the solvent compared to aqueous solvents.

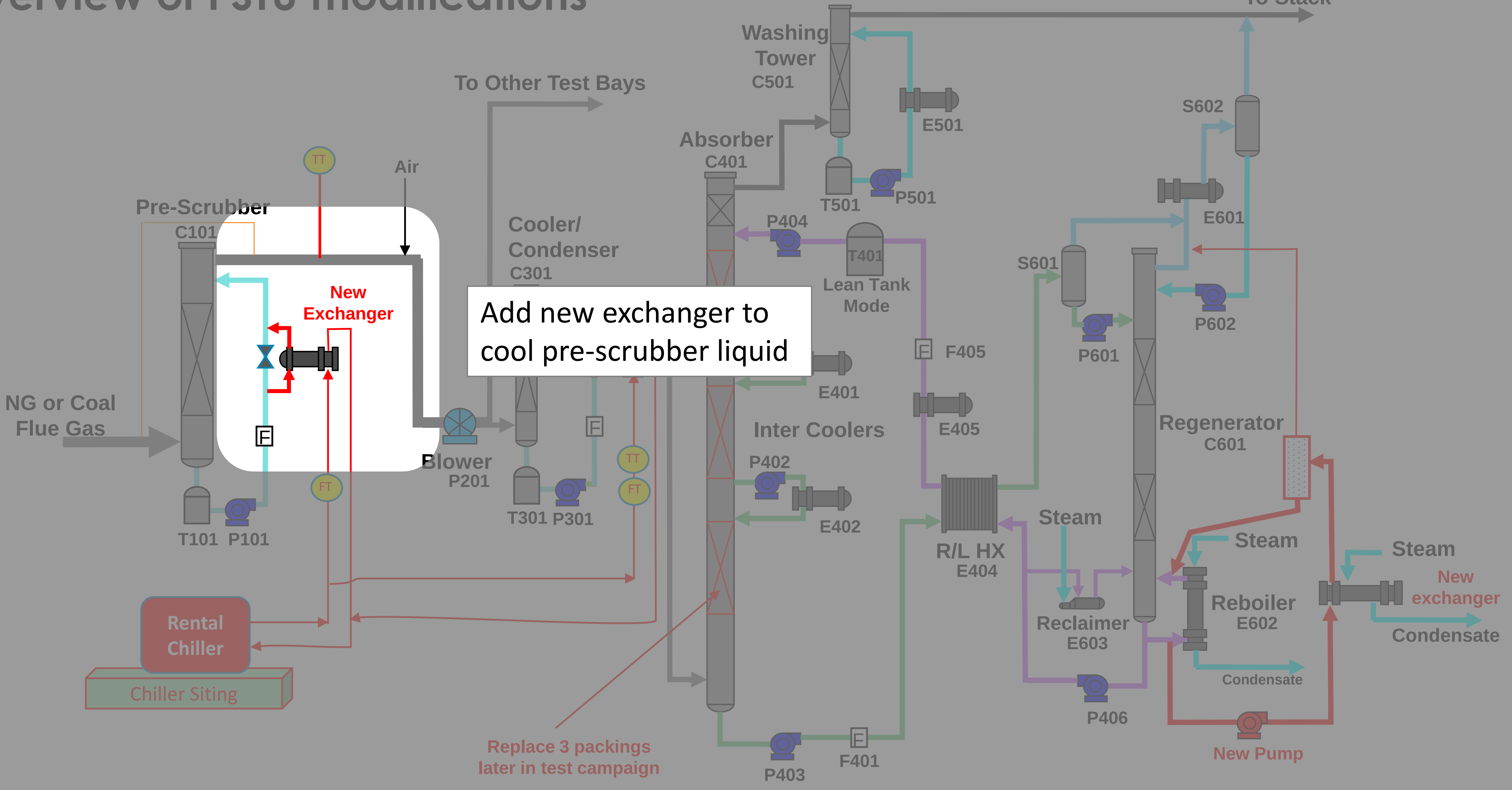
Overview of PSTU modifications



Courtesy of Southern Company Services

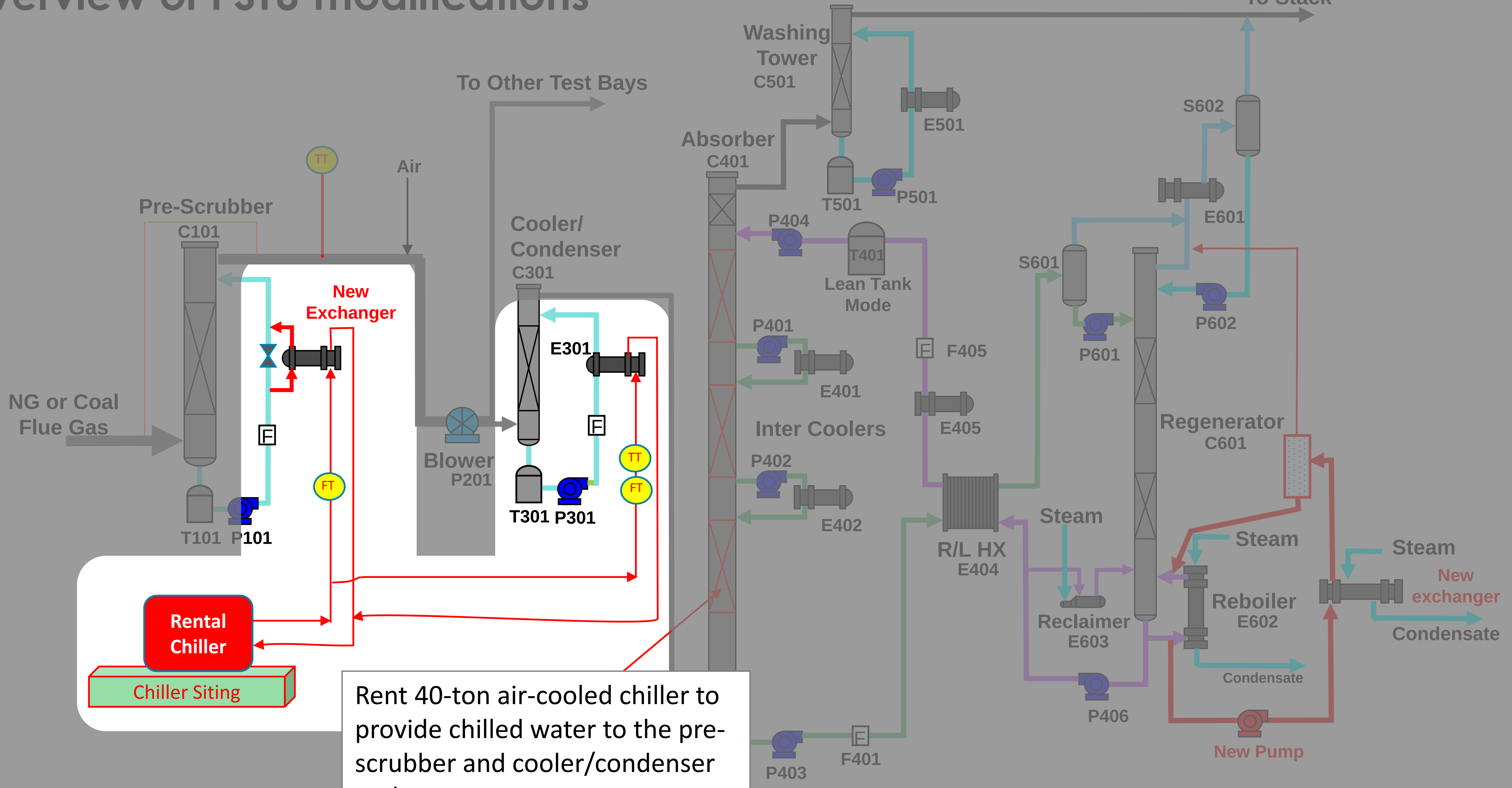
Overview of PSTU modifications

Add new exchanger to cool pre-scrubber liquid



Courtesy of Southern Company Services

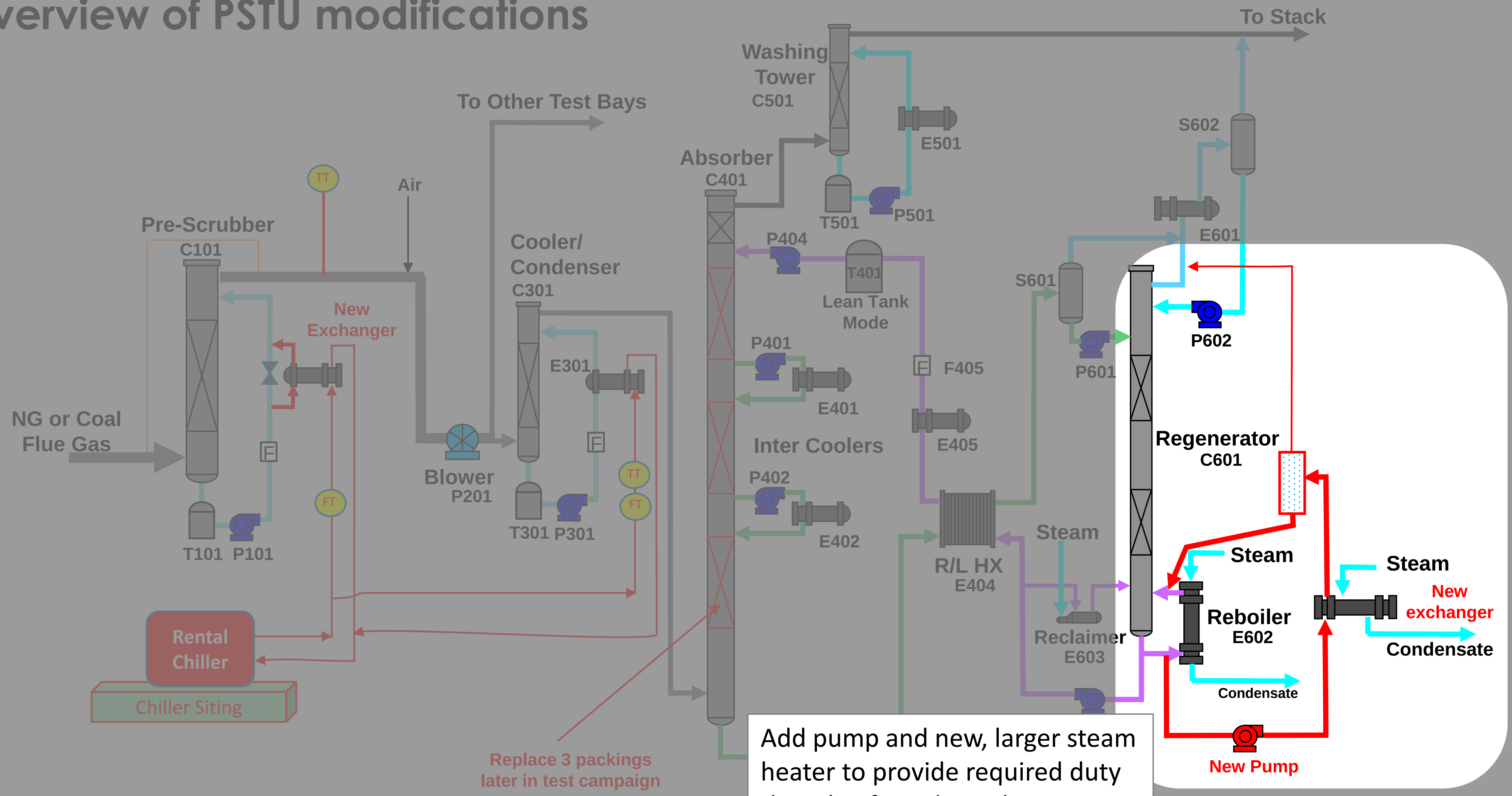
Overview of PSTU modifications



Rent 40-ton air-cooled chiller to provide chilled water to the pre-scrubber and cooler/condenser exchangers.

Courtesy of Southern Company Services

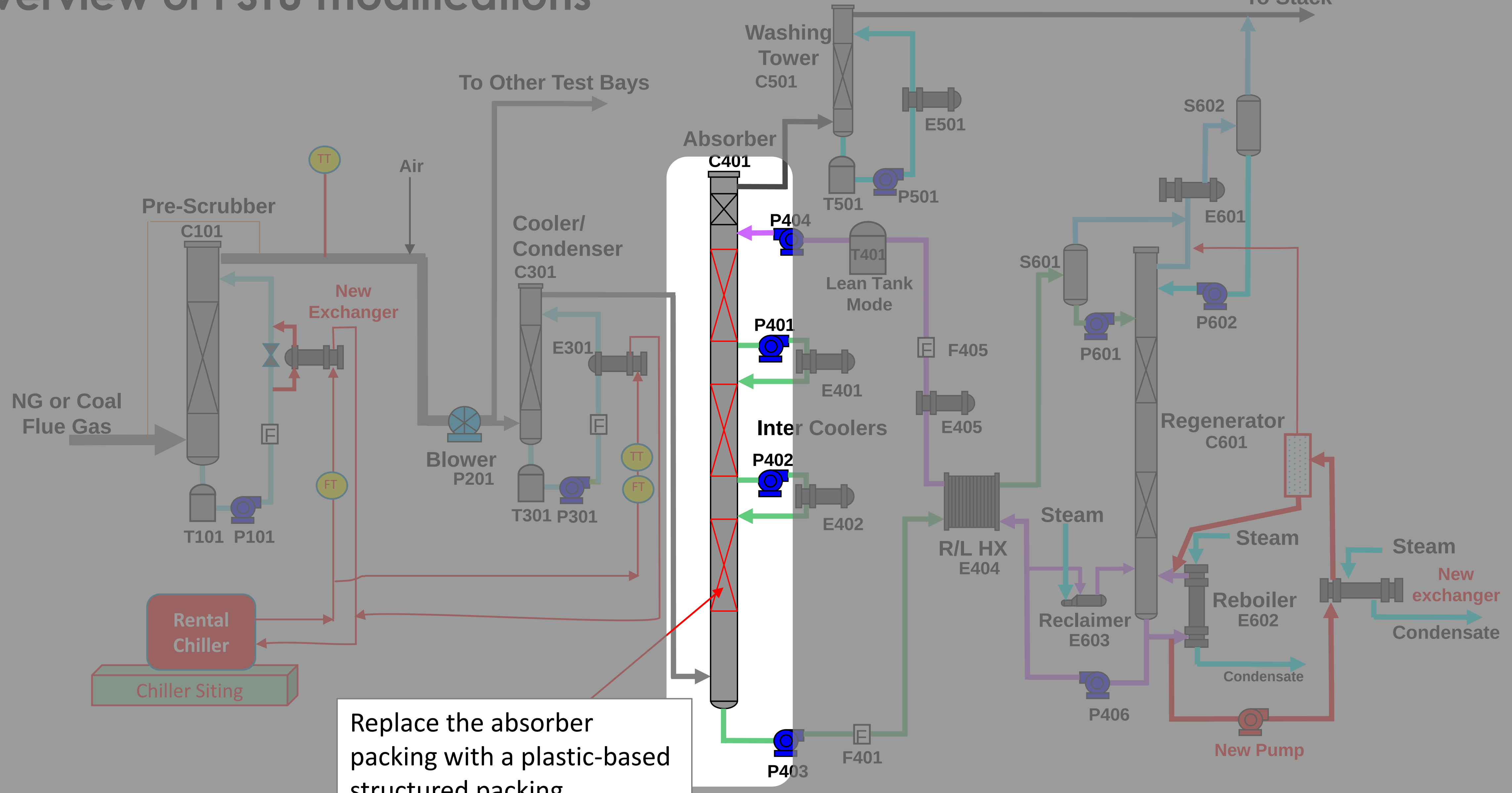
Overview of PSTU modifications



Add pump and new, larger steam heater to provide required duty though a forced circulation reboiler.

Courtesy of Southern Company Services

Overview of PSTU modifications



Replace the absorber packing with a plastic-based structured packing.

Courtesy of Southern Company Services

Design of engineering-scale test

Plastic packing

- Different packing manufacturers were interviewed to determine different options.
- A polypropylene packing comparable to the existing PSTU was selected.
- The current plan is to conduct testing with both the current packing and plastic to help provide a comparison.

Safety

- A Safety Data Sheet for EEMPA has been compiled using the expected composition based on the chosen synthesis route. A look-across analysis was performed
- HAZOP/DHR exercise was performed 6/29. One safety related issue was identified and a preliminary mitigation proposed.

Next project phases

Budget Period 2

- Manufacture ≈2,000 gallons of EEMPA
- Make modifications to the PSTU to support EEMPA’s testing
  - Chiller loop installation
  - Regenerator enhancements
- Develop a comprehensive test plan
  - Working with CCSI2 to develop a structured test plan using sequential design of experiments to help achieve

Budget Period 3

- Commissioning and parametric testing
- Testing with metal packing
- Testing with plastic packing
- Testing flue gas campaigns for both natural gas and coal flue gas
- Project final techno-economic analysis
- Project final environmental health and safety analysis

Key Points

Solvent synthesis

Found multiple potential synthesis routes, but moving forward with the existing route to protect the project schedule to the greatest extent possible.

Test engineering

Developed a plan to modify the PSTU. Moving forward on implementing that plan.

Next steps

Moving toward a start of testing in early 2024.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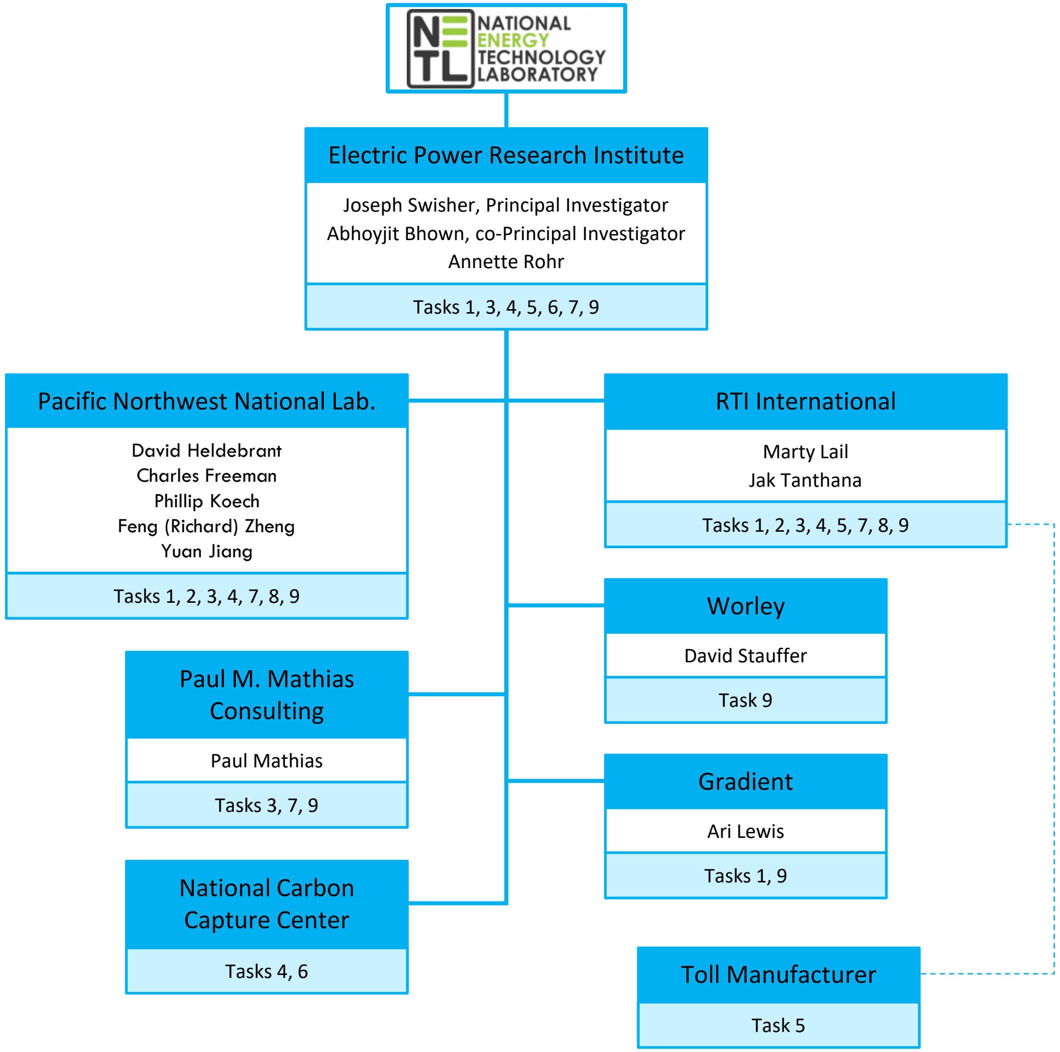
Project organization chart with key personnel



All BPs	
Task 1	Project management and planning
Budget Period 1	**Solvent scale-up and design of engineering scale test equipment**
Task 2	Scale-up of solvent production
Task 3	Design of Engineering Scale Test Equipment
Task 4	Host site planning
Budget Period 2	**Solvent manufacture and test facility modification**
Task 4	Host site planning
Task 5	Manufacture of solvent
Task 6	Construction at host site
Task 7	Test plan development
Budget Period 3	**Testing and data analysis**
Task 8	Operation of Engineering Scale Test
Task 9	Data Analysis and Final Reporting

Gantt chart

ID	Task Name	Start	Finish
1	**Project management and planning**	**Fri 1/29/21**	**Mon 6/30/**
2	Project Management Plan updates	Fri 1/29/21	Mon 6/30/
3	*Revised PMP provided to DOE/NETL*	*Sun 2/28/2*	*Sun 2/28/2*
4	Technology Maturation Plan	Mon 2/1/2	Fri 4/30/21
5	Initial Techno-economic analysis and EH&S review	Mon 2/1/21	Fri 4/30/21
6	*TMP, initial TEA, and initial EH&S assessment delivered to DOE/NETL*	*Fri 4/30/21*	*Fri 4/30/21*
7	**Scale-up of solvent production**	**Mon 2/1/2**	**Sun 4/30/2**
8	Determine best synthesis route for larger scale	Mon 2/1/21	Tue 1/31/23
9	*Synthesis route developed that can meet $10/kg cost target with expected reagent and manufacturing costs.*	*Wed 2/15/23*	*Wed 2/15/23*
10	Setup process for larger-scale synthesis	Thu 7/1/21	Sun 4/30/2
11	*Toll manufacturer identified. Cost and availability of reagents verified to meet project budget and schedule.*	*Fri 3/31/23*	*Fri 3/31/23*
12	**Design of Engineering Scale Test Equipment**	**Thu 4/1/21**	**Fri 3/31/23**
13	Adapt models to evaluate test design	Thu 4/1/21	Fri 3/31/23
14	Design and specify equipment	Thu 7/1/21	Fri 3/31/23
15	Develop construction cost and plan	Wed 9/1/2	Fri 3/31/23
16	*Models developed to assist in the engineering of the test equipment. Engineering and equipment selection completed. Plan for procurement and developed with a cost estimate within project budget.*	*Tue 2/28/23*	*Tue 2/28/23*
17	**Host site planning**	**Thu 4/1/21**	**Tue 10/31/**
18	Conduct design hazard review	Thu 4/1/21	Fri 6/30/23
19	*Design Hazard Review completed.*	*Fri 6/30/23*	*Fri 6/30/23*
20	Exectute host site agreement	Tue 6/1/21	Tue 10/31/
21	*Host Site Agreement with signed cover letter indicating agreement with design, DHR, and schedule*	*Tue 10/31/23*	*Tue 10/31/23*
22	Permitting	Wed 9/1/2	Sun 4/30/2
23	*Required permits have been identified and a plan for ensuring their issuance was assembled.*	*Tue 2/28/23*	*Tue 2/28/23*
24	**Go/No Go: Solvent manufacturing plan and host site modification plans**	**Fri 6/30/23**	**Fri 6/30/23**
25	**Manufacture of solvent**	**Sun 10/1/2**	**Thu 2/29/2**
26	Procurement of raw materials	Sun 10/1/2	Mon 1/1/2
27	*Trial batch of solvent meets specifications for final manufacturing.*	*Wed 11/1/23*	*Wed 11/1/23*
28	Production and delivery to host site	Wed 11/1/	Thu 2/29/2
29	**Construction at host site**	**Sat 7/1/23**	**Wed 1/31/**
30	Planning and safety	Sat 7/1/23	Wed 1/31/
31	Procurement of equipment	Sat 7/1/23	Sun 12/31/
32	Construction activities at the host site	Fri 9/1/23	Wed 1/31/
33	*Equipment modification and installation activities completed at host site.*	*Wed 1/31/24*	*Wed 1/31/24*
34	**Test plan development**	**Sat 7/1/23**	**Wed 1/31/**
35	*Test plan completed and submitted to host site and DOE/NETL for review and approval.*	*Mon 1/15/24*	*Mon 1/15/24*
36	**Go/No Go: Solvent manufactured and modifications completed.**	**Thu 2/29/24**	**Thu 2/29/24**
37	**Operation of Engineering Scale Test**	**Fri 3/1/24**	**Tue 12/31/**
38	Shakedown and commissioning	Fri 3/1/24	Fri 3/22/24
39	Parametric testing	Mon 3/25/	Fri 4/19/24
40	Coal flue gas campaign	Mon 4/22/	Mon 7/22/
41	*Coal flue gas campaign competed with at least two months of operation.*	*Mon 7/15/24*	*Mon 7/15/24*
42	Natural gas flue gas campaign	Tue 7/23/2	Tue 10/15/
43	*Natural gas campaign completed with at least two months of operation.*	*Tue 10/15/24*	*Tue 10/15/24*
44	De-mobilization, removal and/or disposal of solvent	Wed 10/16/24	Thu 11/14/24
45	**Data Analysis and Final Reporting**	**Mon 4/1/2**	**Wed 10/29/**
46	Analysis of test campaign results	Mon 4/1/2	Mon 3/3/2
47	Final TEA	Tue 10/1/2	Mon 6/30/
48	Final EH&S Assessment	Tue 10/1/2	Mon 6/30/
49	*Updated State Point Data Table*	*Mon 6/30/*	*Mon 6/30/*
50	*Draft Final Report*	*Mon 6/30/*	*Mon 6/30/*
51	*Final reports delivered to DOE/NETL within 90 days of project close.*	*Tue 9/30/25*	*Tue 9/30/25*