

# Bench-scale Development of a Transformational Graphene Oxide-based Membrane Process for Post-combustion CO<sub>2</sub> Capture

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#### **Project overview**

- **Performance period**: June 1, 2018 September 30, 2022
- **Funding**: \$2,914,074 from DOE; \$728,738 cost share
- <u>Objective</u>: Develop a transformational graphene oxide (GO)-based membrane process (GO<sup>2</sup>) for CO<sub>2</sub> capture with 95% CO<sub>2</sub> purity and a cost of electricity (COE) at least 30% lower than DOE amine reference baseline SC PC plant case



#### GO membrane technology based on our work published in Science, Nature Communications, and Journal of Membrane Science



Ultrathin, Molecular-Sieving Graphene Oxide Membranes for Selective Hydrogen Separation Hang Li et al. Science **342**, 95 (2013); DOI: 10.1126/science.1236686



#### **Contribution**:

- Single-layered GO flake prepared as thin as 1 nm
- Structural defects on GO flakes can be controlled as transport pathway for selective gas separations

## nature

#### ARTICLE

#### DOI: 10.1038/s41467-017-02318-1 OPEN

Ultrathin graphene oxide-based hollow fiber membranes with brush-like CO<sub>2</sub>-philic agent for highly efficient CO<sub>2</sub> capture



Journal of Membrane Science Volume 573, 1 March 2019, Pages 184-191



Ultrathin, ethylenediamine-functionalized graphene oxide membranes on hollow fibers for CO<sub>2</sub> capture



## **Process description**

50–70% removal from coal flue gas: single stage



 70–90% removal from coal or natural gas flue gases: a proprietary GO<sup>2</sup> process integrates a high-selectivity GO-1 membrane and a high-flux GO-2 membrane for optimal performance



### Scalable procedures developed for fabricating GO membranes



Hollow fiber support GO-based coating solution flows inside the hollow fiber

GO membrane on hollow fiber

Flat sheet membranes: Spray coating



# An innovative membrane structure: GO nanochannels intercalated by single-walled carbon nanotubes

What does this structure look like?



- Why this structure?
  - SWCNTs narrow surface pore size below GOQD size
  - Infiltrated GOQDs pack densely with SWCNTs to form a carbon-based hybrid membrane

SWCNT = single-walled carbon nanotube; N-GOQD = nitrogen-doped graphene oxide quantum dot

### **High-quality GO-based membranes prepared on the** commercial available PES hollow fiber substrates

Hollow fiber inner diameter: 1 mm



Surface of the substrate: skin layer with pore size of 50-200 nm

Surface and cross section of the N-GOQD/SWCNT/ **DETA** membrane

# GO-1 membrane showed CO<sub>2</sub>/N<sub>2</sub> selectivity of 300 with CO<sub>2</sub> permeance of 1,100 GPU at 80°C during 50-h testing

- Flat sheet membrane
- Membrane: GO/PEI/DETA
- Testing conditions:
  - Feed mixture: 8.0 vol% CO<sub>2</sub>, 45.2 vol% N<sub>2</sub>, and 46.8 vol% H<sub>2</sub>O
  - Temperature: 80°C
  - Feed pressure: ~1.0 bara
  - Permeate side pressure:
     0.40 bara



GO = graphene oxide; PEI = polyethylenimine; DETA = diethylenetriamine
 GPU = Gas Permeation Unit (1 GPU = 3.348 x 10<sup>-10</sup> mol/m<sup>2</sup>/s/Pa)

# GO-2 membrane showed $CO_2$ permeance of 2,400 GPU with $CO_2/N_2$ selectivity of 125 at 80°C during 100-h testing

- Flat sheet membrane
- Membrane: GOQD/CNT/DETA
- Testing conditions:
  - Feed mixture: 4.0 vol% CO<sub>2</sub>, 49.2 vol% N<sub>2</sub>, and 46.8 vol% H<sub>2</sub>O
  - Temperature: 80°C
  - Feed pressure: ~1.0 bara
  - Permeate side pressure:
     0.30 bara





GOQD = graphene oxide quantum dot; CNT = carbon nanotube; DETA = diethylenetriamine; GPU = Gas Permeation Unit (1 GPU = 3.348 x 10<sup>-10</sup> mol/m<sup>2</sup>/s/Pa)

# Scaleup of GO-based membranes on commercially available 1,000 cm<sup>2</sup> hollow fiber substrates



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# 1,000 cm<sup>2</sup> membrane showed CO<sub>2</sub> permeance of 984 GPU with CO<sub>2</sub>/N<sub>2</sub> selectivity of 330 during a stage-cut testing

- Membrane: GOQD/CNT/DETA
- Testing condition:
  - Feed mixture: CO<sub>2</sub> 9.1 vol%; N<sub>2</sub> 50.8 vol%; H<sub>2</sub>O 40.1 vol%
  - Temperature: 80°C
  - Feed pressure: ~1 bara
  - Permeate side pressure: 0.40 bara
- CO<sub>2</sub> capture performance:

CO <sub>2</sub> permeance	CO <sub>2</sub> /N <sub>2</sub>	Permeate side CO <sub>2</sub>	CO <sub>2</sub> capture
(GPU)	selectivity	purity (dry base)	rate
984	330	96.6 vol%	40.3%



#### Scaleup of GO-based flat sheet membranes by spray coating

#### 145 cm<sup>2</sup> (14.5 cm x 10 cm) coated



- Membrane: GOQD/CNT/PSS/DETATesting condition:
  - Feed mixture: 15 vol%CO<sub>2</sub>/85 vol%N<sub>2</sub> (saturated with H<sub>2</sub>O)
  - 80°C
  - Feed pressure: ~ 1 bara
  - Permeate pressure: 0.40 bara
  - CO<sub>2</sub> capture performance

Sample	CO <sub>2</sub> permeance, GPU	α <sub>co2/N2</sub>
#1	997	240
#2	1,310	240
#3	998	120
#4	1,020	300
#5	1,030	310
#6	1,240	360
#7	1,130	340
Average	1,100 ± 127	272 ± 81

# Lab testing indicates the presence of NO<sub>2</sub> and O<sub>2</sub> does not affect the CO<sub>2</sub> capture performance of the GO membrane

- Membrane: GOQD/CNT/TEPA-PEI-DETA, area: 51.6 cm<sup>2</sup>
- Testing conditions:

Feed mixture	CO <sub>2</sub> (vol%)	N <sub>2</sub> (vol%)	H <sub>2</sub> O (vol%)	O <sub>2</sub> (vol%)	NO <sub>2</sub> (ppmv)	Feed Pressure (bara)	Permeate pressure (bara)	T (°C)
CO <sub>2</sub> /N <sub>2</sub> /H <sub>2</sub> O	8.0%	45.3%	46.7%	0	0	1	0.4	80
CO <sub>2</sub> /N <sub>2</sub> /H <sub>2</sub> O/O <sub>2</sub> /NO <sub>2</sub>	8.0%	43.7%	46.7%	1.6%	35	1	0.4	80

Testing results:

Feed mixture	CO <sub>2</sub> permeance (GPU)	CO <sub>2</sub> /N <sub>2</sub> selectivity
$CO_2/N_2/H_2O$	$1,490 \pm 34$	200 ± 10
CO <sub>2</sub> /N <sub>2</sub> /H <sub>2</sub> O/O <sub>2</sub> /NO <sub>2</sub>	$1,450 \pm 29$	$190 \pm 3.0$



CNT = carbon nanotube; GOQD = graphene oxide quantum dot; TEPA: tetraethylenepentamine; PEI = polyethylenimine; DETA = diethylenetriamine  $^{13}$  GPU = Gas Permeation Unit (1 GPU = 3.348 x 10<sup>-10</sup> mol/m<sup>2</sup>/s/Pa)

### Preliminary testing data indicate membrane performance not affected by SO<sub>2</sub>

- Tests conducted with two fresh membranes: one with SO<sub>2</sub> in feed, another without SO<sub>2</sub> in feed
  - Feed mixture: CO<sub>2</sub>: N<sub>2</sub>: O<sub>2</sub>: H<sub>2</sub>O = 12.8 %: 38.9%: 1.6%: 46.7% in vol%; SO<sub>2</sub>: 46 ppm
  - Temperature: 80°C; Feed pressure: ~1 bara; Permeate side pressure: 0.44 bara
- Similar transient permeation behavior: membrane performance reached steady state in ~2 h after vacuum was introduced to the permeate
- Taking into account of membrane variations and testing error bar (±10%), CO<sub>2</sub> permeances and CO<sub>2</sub>/N<sub>2</sub> selectivities calculated from two tests (with and without SO<sub>2</sub>) were identical

Test condition	CO <sub>2</sub> permeance (GPU)	N <sub>2</sub> permeance (GPU)	CO <sub>2</sub> /N <sub>2</sub> selectivity
Without SO <sub>2</sub>	961	4.68	205
With SO <sub>2</sub>	1060	5.19	204

 Steady-state stability (≥100 h) will be further investigated under Task 6 with scaled membranes (500-1,000 cm<sup>2</sup>)

### Where do our membranes fall on the Robeson plots?



**gti**.

Robeson, J. Membrane Sci. **2008**, Vol. 320, p390 Note: Polymer data points (red): 100 nm membrane thickness assumed

### Future work of this project

 Task 1
 Project management and planning (throughout the project)



## **Technology development path**



## **Summary**

- We are developing a transformational graphene oxide-based membrane process for post-combustion CO<sub>2</sub> capture
  - **Single stage** for 50–70% removal from coal flue gas
  - GO<sup>2</sup> process integrating a high-selectivity GO-1 membrane and a high-flux GO-2 membrane for 70–90% removal from coal or natural gas flue gases
- An innovative membrane structure was developed and showed high CO<sub>2</sub> capture performance and good stability
- Preliminary lab tests indicated GO-based membranes stable in the presence of O<sub>2</sub>, NO<sub>2</sub> and SO<sub>2</sub>
- Membranes scaled to 1,000 cm<sup>2</sup> surface area. The performance of the scaled membranes achieved technical goals
- A bench-scale system is under design and will be tested at NCCC

# Acknowledgements

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NATIONAL CARBON CAPTURE CENTER



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- DOE NETL: Dustin Brown, Andrew O'Palko, José Figueroa, Dan Hancu and Lynn Brickett
- The CCP4: Betty Pun and Mark Crombie
- NCCC: Frank Morton and Tony Wu



### **Appendix – Organization Chart**





### **Appendix – Gantt Chart**

#### BP1

#### **BP2**

ID	Task	Sub-T	MS	Task or Milestone Description	Start	Finish	Task Total	20 Q1	18 2019 2020 2021   02   03   04   01   04   01   04   01   04   04	2022
1				Total Project	Tue 5/1/18	Mon 8/1/22	\$3,642,857	1	I	
2	1.0			Project management and planning	Tue 5/1/18	Mon 8/1/22	\$286,973	5	I	
3			1.1	Updated Project Management Plan	Mon 10/1/18	Fri 11/30/18			11/30	
4			1.2	Kickoff Meeting	Mon 10/1/18	Tue 1/15/19			1/15	
5			1.3	Technology maturation plan submitted to DO	Mon 10/1/18	Tue 1/15/19			1/15	
6			1.4	Continuation applicatoin for BP2 submitted	Sun 12/1/19	Tue 12/31/19			12/31	
7			1.5	Submit BP1 report	Wed 4/1/20	Thu 4/30/20			♦ 4/30	
8			1.6	Submit final technical report	Fri 10/1/21	Fri 12/30/22				12/30
9	2.0			Development of GO membrane with area of 50-100 cm2	Mon 10/1/18	Sun 6/30/19	\$358,884	L		
10		2.1		Fabrication of GO hollow fiber membranes by vacuum filtration	Mon 10/1/18	Sun 6/30/19				
11		2.2		Fabrication of flat sheet GO membranes by printing	Mon 10/1/18	Sun 6/30/19				
12			2.1	50-100 cm2 GO membranes prepared	Mon 10/1/18	Wed 1/30/19			1/30	
13			2.2	For 50-100 cm2 area membranes, GO-1 exhibits CO2/N2 selectivity $\ge$ 100 and CO2 permeance $\ge$ 1,000 GPU and GO-2 exhibits CO2/N2 selectivity $\ge$ 10 and CO2 permeance	Fri 2/1/19	Sun 6/30/19			♦ 6/30	
14	3.0			Improvement of preparation conditions for 50-100 cm2 GO membranes towards higher selectivities	Mon 7/1/19	Tue 3/31/20	\$550,225	5		
15		3.1		Fabrication of GO hollow fiber membranes by vacuum filtration	Mon 7/1/19	Tue 3/31/20				
16		3.2		Fabrication of flat sheet GO membranes by printing	Mon 7/1/19	Tue 3/31/20				
17			3.1	For 50-100 cm2 area membranes, GO-1 exhibits CO2/N2 selectivity ≥200 and CO2 permeance ≥1,000 GPU and GO-2 exhibits CO2/N2 selectivity ≥20 and CO2 permeance	Mon 7/1/19	Fri 2/28/20			◆ 2/28	
18	4.0			Performance stability testing of GO membranes at near realistic flue gas	Tue 10/1/19	Tue 3/31/20	\$207,864	L		
19			4.1	Stability testing shows the CO2 permeances and CO2/N2 selectivities decreased by less than 10% in the presence of flue gas	Tue 10/1/19	Tue 3/31/20			♦ 3/31	
20				End of BP1 (5/1/18-3/31/20)						

21         5.0         Scale-up of GO membrane modules to effective areas of 1000 cm2         Wed 4/1/20         Fri 12/31/21         \$572,444           22         5.1         Fabrication of GO hollow fiber membranes painting         Wed 4/1/20         Fri 12/31/21         \$159,626           23         5.2         Fabrication of GO hollow fiber membranes painting         Wed 4/1/20         Fri 12/31/21         \$272,204           24         5.3         Fabrication of giral-wound GO membrane modules         Wed 4/1/20         Fri 12/31/21         \$140,614           25         5.3         For 1000 cm2 area membranes, GO-1 exhibits CO2/N2 selectivity 220 and CO2 permeances 21,000 GPU and GO-2 exhibits CO2/N2 selectivity 220 and CO2 permeance         Wed 4/1/20         Fri 12/31/21         \$221,276           26         6.0         100-h stability tests for GO membranes developed under task 5         Wed 4/1/20         Fri 12/31/21         \$221,276           27         K         6.1         GO2 permeances and CO2/N2 selectivities decrease by less than 10% during a 100-h continuous testing         Wed 7/1/20         Fri 12/31/21         \$341,140           28         7.0         Design and construction of two-stage GO membrane skid         Wed 7/1/20         Thu 9/30/21         \$50,548           30         7.2         Construction of membrane skid         Thu 10/1/20         Wed 7/1/20								
22       5.1       Fabrication of G0 hollow fiber membranes       Wed 4/1/20       Fri 12/31/21       \$159,626         23       5.2       Fabrication of flat sheet G0 membranes by printing       Wed 4/1/20       Fri 12/31/21       \$272,204         24       5.3       Fabrication of spiral-wound G0 membrane modules       Wed 4/1/20       Fri 12/31/21       \$140,614         25       5.3       Fabrication of spiral-wound G0 membrane modules       Wed 4/1/20       Fri 12/31/21       \$140,614         26       6.0       1       5.1 For 1000 cm2 area membranes, G0-1 exhibits       Wed 4/1/20       Fri 12/31/21       \$221,276         26       6.0       1       10-0-1 stability tests for G0 membrane skid       Wed 4/1/20       Fri 12/31/21       \$221,276         27       6.1       C02 permeances and C02/N2 selectivities decrease by less than 10% during a 100-h continuous testing       Wed 4/1/20       Fri 12/31/21       \$341,140         29       7.1       Process simulation and design of system       Wed 7/1/20       Fri 12/31/21       \$260,548         30       7.2       Construction of membrane skid       Thu 10/1/20       Wed 7/1/20       Thu 9/30/21       \$280,592         31       1       Conglete process design for low and high constructed 60 system at GTI using natural gas-fired flue gas       \$361/1/22 <td>21</td> <td>5.0</td> <td></td> <td></td> <td>Scale-up of GO membrane modules to effective areas of 1000 cm2</td> <td>Wed 4/1/20</td> <td>Fri 12/31/21</td> <td>\$572,444</td>	21	5.0			Scale-up of GO membrane modules to effective areas of 1000 cm2	Wed 4/1/20	Fri 12/31/21	\$572,444
23       5.2       Image: provincing printing printi printing printing printing printing printing prini pri	22		5.1		Fabrication of GO hollow fiber membranes by vacuum filtration	Wed 4/1/20	Fri 12/31/21	\$159,626
24       5.3       Fabrication of spiral-wound GO membrane modules       Wed 4/1/20       Fri 12/31/21       \$140,614         25       28       28       5.1       For 1000 Cm2 area membranes, GO-1 exhibits CO2/N2 selectivity ≥20 and CO2 permeance       Wed 4/1/20       Thu 9/30/21       S221,276         26       6.0       100-h stability tests for GO membranes developed under task 5       Wed 4/1/20       Fri 12/31/21       \$221,276         27       28       6.1       CO2 permeances and CO2/N2 selectivities decrease by less than 10% during a 100-h continuous testing       Wed 4/1/20       Fri 12/31/21       \$341,140         28       7.0       2       Design and construction of two-stage GO membrane skid       Wed 7/1/20       Fri 12/31/21       \$341,140         29       7.1       Process simulation and design of system       Wed 7/1/20       Thu 9/30/21       \$60,548         30       7.2       Construction of membrane skid       Thu 10/1/20       Wed 12/1/21       \$280,592         31       7.1       Complete process design for low and high CO2 file gas conditions; and process simulation indicates that the CO2 capture system can achieve >95% CO2 purity       Thu 9/30/21       \$280,592         32       7.2       Constructed GO system at GTI using natural gas-fired flue gas       \$311/1/22       Mon 2/28/22       \$91,035         3	23		5.2		Fabrication of flat sheet GO membranes by printing	Wed 4/1/20	Fri 12/31/21	\$272,204
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3132323131313232323232323232323232323232323333313132333133313331333333333333333333353233353233343535323334353334343334 <td>30</td> <td></td> <td>7.2</td> <td></td> <td>Construction of membrane skid</td> <td>Thu 10/1/20</td> <td>Wed 12/1/21</td> <td>\$280,592</td>	30		7.2		Construction of membrane skid	Thu 10/1/20	Wed 12/1/21	\$280,592
32No <td>31</td> <td></td> <td></td> <td>7.1</td> <td>Complete process design for low and high CO2 flue gas conditions; and process simulation indicates that the CO2 capture system can achieve &gt;95% CO2 purity</td> <td>Wed 7/1/20</td> <td>Thu 9/30/21</td> <td></td>	31			7.1	Complete process design for low and high CO2 flue gas conditions; and process simulation indicates that the CO2 capture system can achieve >95% CO2 purity	Wed 7/1/20	Thu 9/30/21	
338.0S.0Testing of GO system at GTI using natural gas-fired flue gasSat 1/1/22Mon 2/28/22\$91,03534S.195% CO2 purity achieved when testing the constructed GO system using natural gas-fired flue gasSat 1/1/22Mon 2/28/22S879,833359.0S.kid installation, commissioning and testing at NCCC using actual flue gasSat 1/1/22Fri 9/30/22\$879,833369.1S.kid installation and commissioning at NCCCTue 3/1/22Wed 3/30/22\$160,427379.2GO membrane support from RPISat 1/1/22Fri 9/30/22\$281,555389.3GO membrane support from OSUSat 1/1/22Fri 9/30/22\$282,555399.4CO2 capture testing of the GO2 system at NCCC using actual flue gasFri 4/1/22Fri 9/30/22\$355,286409.1S.1CO2 commissioning complete and system ready for testing at NCCCTue 3/1/22Thu 3/31/22\$355,2864189.21000 m2 GO membrane modules shipped to NCCCTue 3/1/22Thu 3/31/22Fri 9/30/22\$355,2864289.3Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good 	32			7.2	Constructed skid ready for testing	Wed 7/1/20	Fri 12/31/21	
34       Non 2/28/22       Mon 2/28/22         35       9.0       Non 2/28/22       Skid installation, commissioning and testing the gas       Sat 1/1/22       Fri 9/30/22       \$879,833         36       9.0       Non 2/28/22       Fri 9/30/22       Skid installation, commissioning and testing the gas       Sat 1/1/22       Fri 9/30/22       \$879,833         36       9.1       4       Skid installation and commissioning at NCCC       Tue 3/1/22       Wed 3/30/22       \$160,427         37       9.2       9.2       Go membrane support from RPI       Sat 1/1/22       Fri 9/30/22       \$281,555         38       9.3       Go membrane support from OSU       Sat 1/1/22       Fri 9/30/22       \$82,565         39       9.4       GO commissioning complete and system read provide for testing at NCCC using actual flue gas       Fri 4/1/22       Fri 9/30/22       \$355,286         40       9.4       9.2       1000 m2 GO membrane modules shipped to for testing at NCCC       Tue 3/1/22       Thu 3/31/22       \$355,286         41       10.8       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22       \$355,286         42       11.8       9.3       Skid testing at NCCC complete, 70-90% CO2       Sun 5/1/22       Sin 3/1/24       \$10.0	33	8.0			Testing of GO system at GTI using natural gas-fired flue gas	Sat 1/1/22	Mon 2/28/22	\$91,035
359.0NSkid installation, commissioning and testing at NCCC using actual flue gasSat 1/1/22Fri 9/30/22\$879,833369.1Skid installation and commissioning at NCCCTue 3/1/22Wed 3/30/22\$160,427379.2GO membrane support from RPISat 1/1/22Fri 9/30/22\$281,555389.3GO membrane support from OSUSat 1/1/22Fri 9/30/22\$82,565399.4CO2 capture testing of the GO2 system at NCCC using actual flue gasFri 4/1/22Fri 9/30/22\$355,286409.1Commissioning complete and system ready for testing at NCCCTue 3/1/22Thu 3/31/22\$355,286419.2100 0m2 GO membrane modules shipped to NCCCTue 3/1/22Thu 3/31/22Fri 9/30/22\$4004289.3Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testingSun 5/1/22Fri 9/30/22\$133,1834410.Issue TEA reportSun 5/1/22Fri 9/30/22\$133,183	34			8.1	95% CO2 purity achieved when testing the constructed GO system using natural gas-fired flue gas	Sat 1/1/22	Mon 2/28/22	
36       9.1       4       Skid installation and commissioning at NCCC       Tue 3/1/22       Wed 3/30/22       \$\$160,427         37       9.2       4       GO membrane support from RPI       Sat 1/122       Fri 9/30/22       \$\$281,555         38       9.3       4       GO membrane support from OSU       Sat 1/1/22       Fri 9/30/22       \$\$281,555         39       9.4       8       GO zapture testing of the GO2 system at NCCC using actual flue gas       Fri 9/30/22       \$\$355,286         40       9.4       CO2 capture testing of the GO2 system at NCCC complete and system ready for testing at NCCC       Tue 3/1/22       Thu 3/31/22       \$\$355,286         41       0       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22       \$\$10,0       \$\$100 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Fri 9/30/22       \$\$10,0       \$\$100 m2 GO membrane modules shipped to NCCC       \$\$10,0	35	9.0			Skid installation, commissioning and testing at NCCC using actual flue gas	Sat 1/1/22	Fri 9/30/22	\$879,833
37       9.2       GO membrane support from RPI       Sat 1/1/22       Fri 9/30/22       \$281,555         38       9.3       GO membrane support from OSU       Sat 1/1/22       Fri 9/30/22       \$82,565         39       9.4       CO2 capture testing of the GO2 system at NCCC using actual flue gas       Fri 4/1/22       Fri 9/30/22       \$355,286         40       9.1       Commissioning complete and system ready for testing at NCCC       Tue 3/1/22       Thu 3/31/22       Thu 3/31/22         41       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22       Fri 9/30/22       Fri 9/30/22         42       9.3       Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22       Fri 9/30/22         43       10.0       4       Technical and economic study       Sun 5/1/22       Fri 9/30/22       \$133,183         44       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22       \$133,183	36		9.1		Skid installation and commissioning at NCCC	Tue 3/1/22	Wed 3/30/22	\$160,427
38       9.3       GO membrane support from OSU       Sat 1/1/22       Fri 9/30/22       \$82,565         39       9.4       9.4       CO2 capture testing of the GO2 system at NCCC using actual flue gas       Fri 4/1/22       Fri 9/30/22       \$355,286         40       6       9.4       0       100 m2 GO membrane modules shipped to NCCC       Thu 3/31/22       Thu 3/31/22         41       8       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22       Fri 9/30/22         42       8       9.3       Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22       Fri 9/30/22         43       10.0       4       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22       \$133,183	37		9.2		GO membrane support from RPI	Sat 1/1/22	Fri 9/30/22	\$281,555
39       9.4       9.4       CO2 capture testing of the GO2 system at NCCC using actual flue gas       Fri 4/1/22       Fri 9/30/22       \$355,286         40       a       9.1       Commissioning complete and system ready for testing at NCCC       Tue 3/1/22       Thu 3/31/22         41       a       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22         42       a       9.3       Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22         43       10.0       a       Technical and economic study       Sun 5/1/22       Fri 9/30/22       \$133,183         44       u       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22       \$133,183	38		9.3		GO membrane support from OSU	Sat 1/1/22	Fri 9/30/22	\$82,565
40       9.1       Commissioning complete and system ready for testing at NCCC       Tue 3/1/22       Thu 3/31/22         41       9.2       1000 m2 GO membrane modules shipped to NCCC       Tue 3/1/22       Thu 3/31/22         42       9.3       Skid testing at NCCC complete, 70-90% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22         43       10.0       4       Technical and economic study       Sun 5/1/22       Fri 9/30/22         44       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22	39		9.4		CO2 capture testing of the GO2 system at NCCC using actual flue gas	Fri 4/1/22	Fri 9/30/22	\$355,286
41       9.2       1000 m2 GO membrane modules shipped to NCC       Tue 3/1/22       Thu 3/31/22         42       9.3       Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22         43       10.0       Technical and economic study       Sun 5/1/22       Fri 9/30/22       \$133,183         44       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22       Fri 9/30/22	40			9.1	Commissioning complete and system ready for testing at NCCC	Tue 3/1/22	Thu 3/31/22	
42       9.3       Skid testing at NCCC complete, 70-90% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing       Sun 5/1/22       Fri 9/30/22         43       10.0       Technical and economic study       Sun 5/1/22       Fri 9/30/22       \$133,183         44       10.       Issue TEA report       Sun 5/1/22       Fri 9/30/22       Fri 9/30/22	41			9.2	1000 m2 GO membrane modules shipped to NCCC	Tue 3/1/22	Thu 3/31/22	
43         10.0         Technical and economic study         Sun 5/1/22         Fri 9/30/22         \$133,183           44         0         10. Issue TEA report         Sun 5/1/22         Fri 9/30/22         Fri 9/30/22	42			9.3	Skid testing at NCCC complete, 70-90% CO2 removal rate achieved, 95% CO2 purity validated, and membrane shows good stability during a 200-h continuous testing	Sun 5/1/22	Fri 9/30/22	
44 10. Issue TEA report Sun 5/1/22 Fri 9/30/22	43	10.0			Technical and economic study	Sun 5/1/22	Fri 9/30/22	\$133,183
	44			10.	Issue TEA report	Sun 5/1/22	Fri 9/30/22	



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