



PROJECT CONTINUATION REQUEST MEETING



CO₂ Capture by Cold Membrane Operation with actual power plant flue gas (DE-FE0013163)

March 9th 2015
T. Chaubey | R&D

Air Liquide: Key information



A world leader in industrial and medical gases

> 50,000 employees

~ \$ 20 billion sales (2013)



Proposed new technology leverages AL strengths

- MEDAL – Established membrane manufacturer for N₂, H₂ and CO₂ applications
- Air Liquide core expertise in gas separation, cryogenics and gas handling

Project Team

■ Project team consists of:

■ **Membrane experts** – Sudhir Kulkarni, David Hasse, Karl Beers (MEDAL), Jean-Marie Gauthier (MEDAL)

■ **Process experts** – Trapti Chaubey, Alex Augustine, Paul Terrien (E&C), Alfredo Velasco (MEDAL)

■ **Modeling expert** – Jiefu Ma

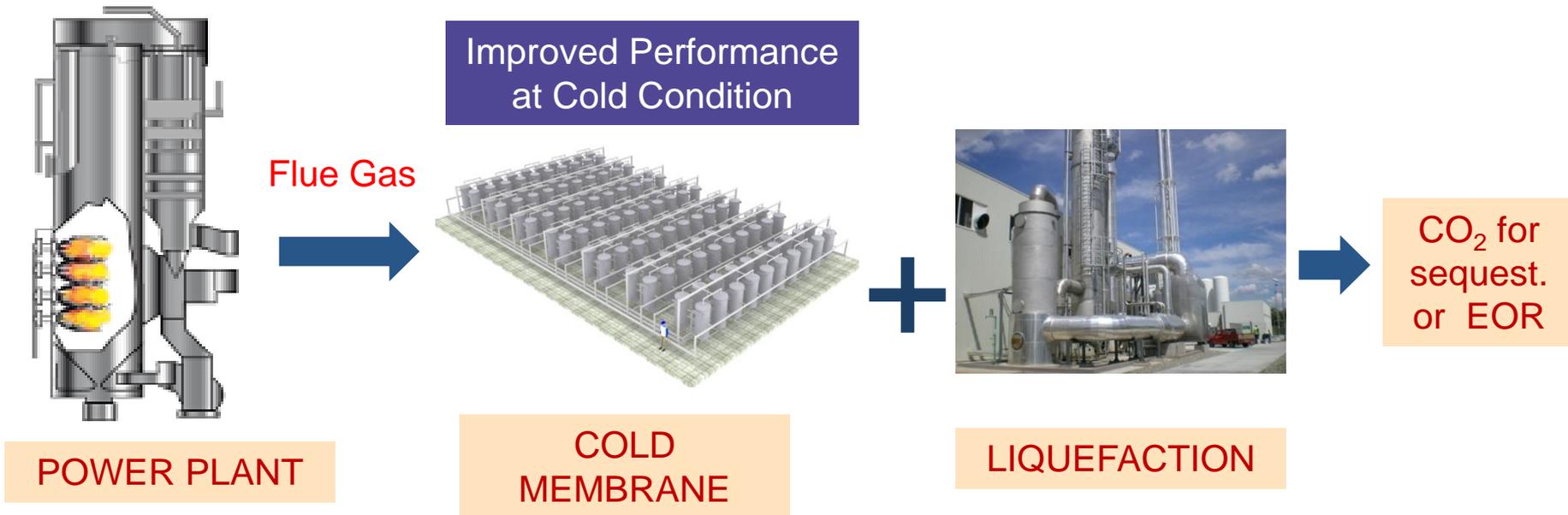
■ **Senior Technicians** – Jacob Brumback, Dean Kratzer, Judy Huss

■ **AL management** – David Edwards, Ed Sanders



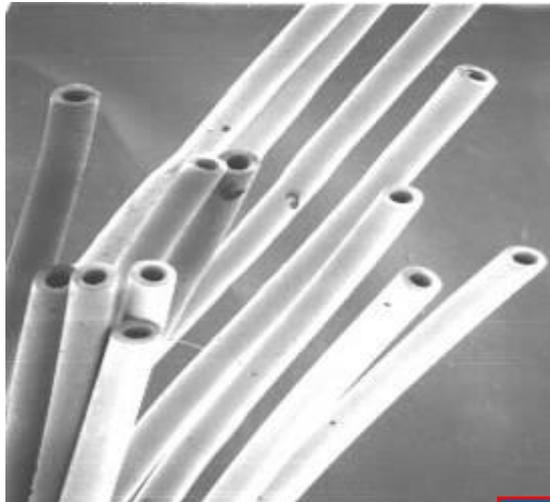
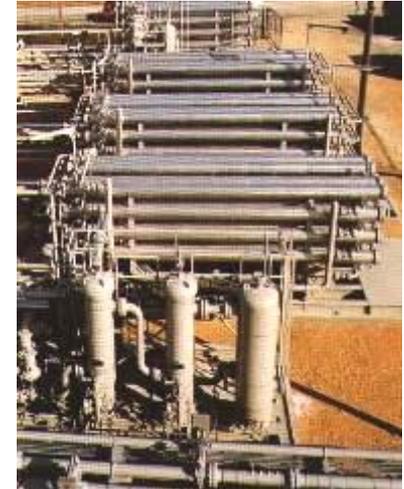
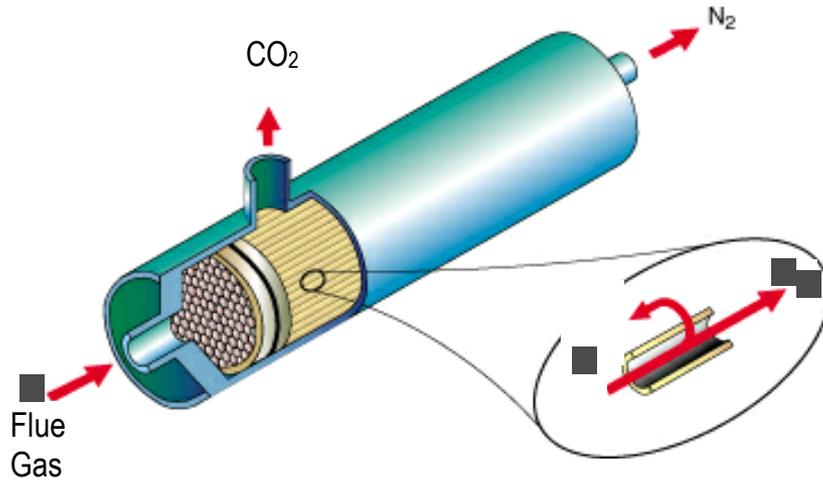
Project Summary

- Air Liquide Hybrid Cold membrane - Liquefaction Process plant for 550 MWe scale



- Cold membrane testing was completed with synthetic flue gas (TRL4) in 2012
 - CO₂ Capture Cost estimated at 46-52\$/tonne (DOE Target - \$40/tonne)
- Current project will test the cold membrane technology with real flue gas at 0.3 MWe (TRL5) using field test unit at National Carbon Capture Center (NCCC)

Cold Membrane Process Based on Existing AL Membrane

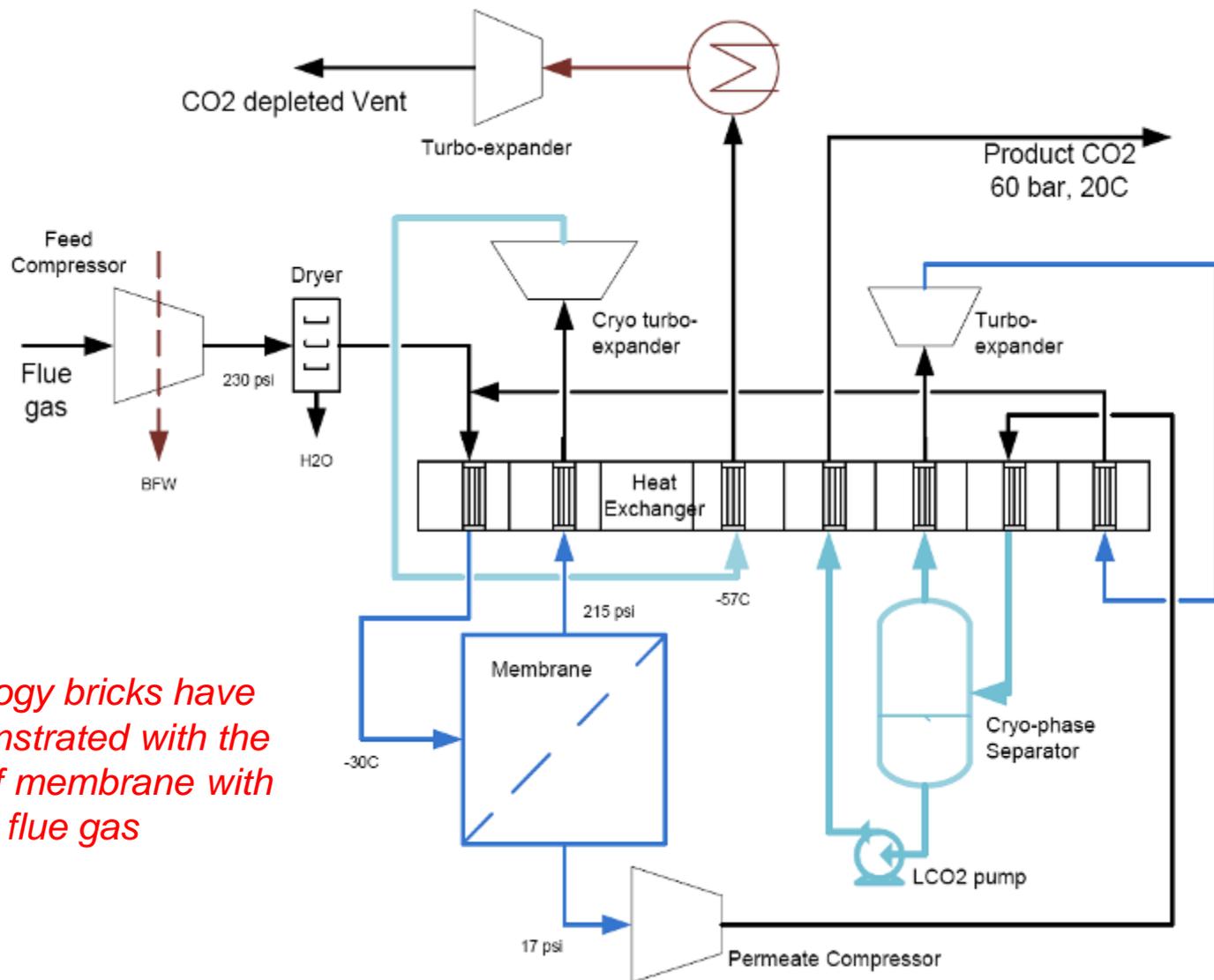


Hollow fiber membranes are providing cost effective solutions (~ \$20/m²) in very large (up to 1 Bscfd) CO₂ separation applications



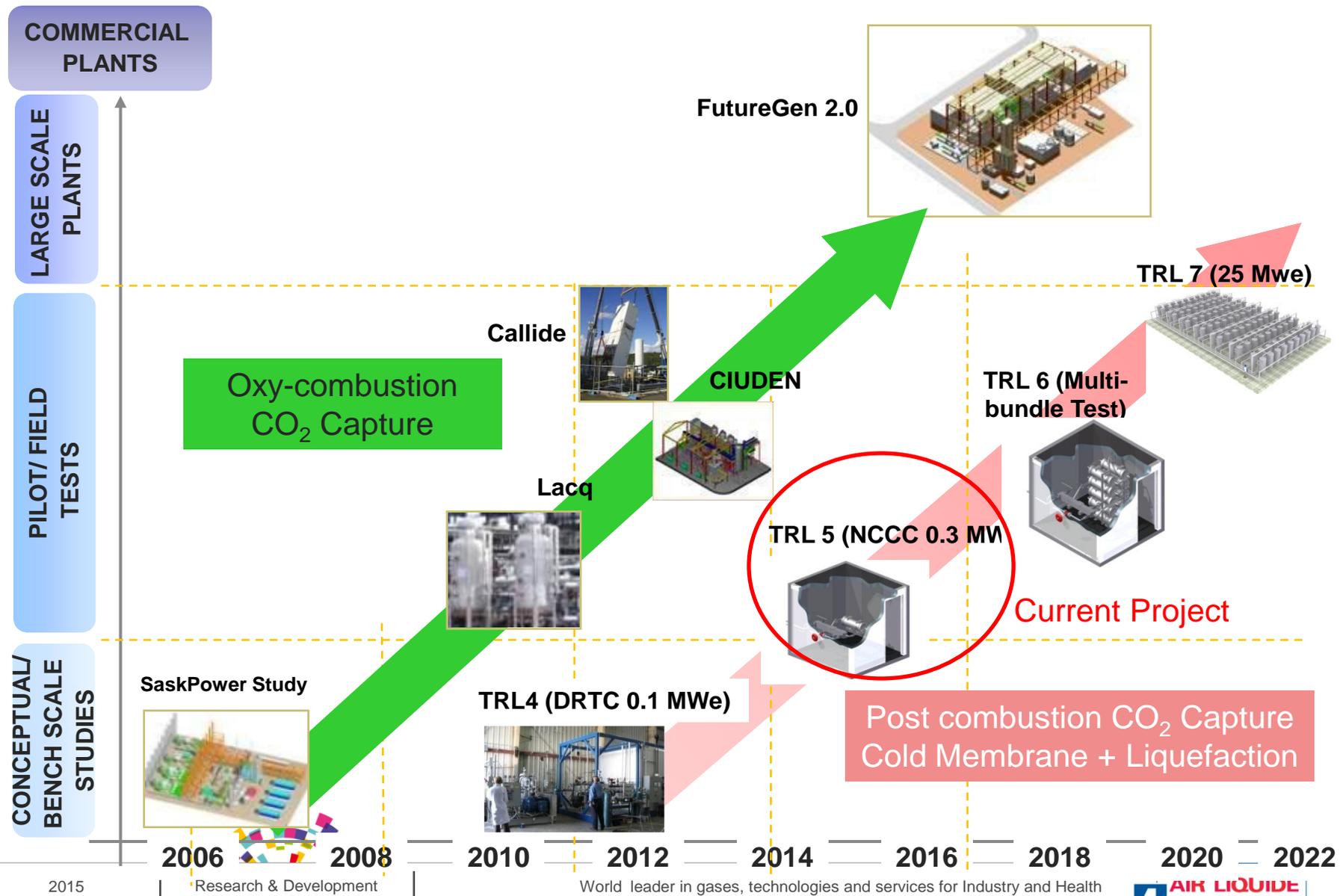
>5X Surface area/volume compared to spiral membranes

Overall Process



All technology bricks have been demonstrated with the exception of membrane with real flue gas

Air Liquide Roadmap for CO₂ Capture Technologies



Project Overview: DOE NETL Award No. DE-FE0013163

Total Budget : \$5.8MM, DOE Funding - \$4.7MM ; Cost share - \$1.1MM

	DOE Share	AL Cost Share
Budget Period 1 (Oct 2013 – March 2015)	\$3,369,528	\$842,382
Budget Period 2 (April 2015 – March 2016)	\$1,338,964	\$334,741

Period of Performance: 10/01/2013 through 3/31/2016 over 2 Budget Periods

NETL Project Manager: José Figueroa

Prime Recipient: American Air Liquide DRTC

Project Sub-awardees: MEDAL (Bundle Optimization support, Detailed engineering), E&C (Basic Engineering & TEA), Parsons (TEA Review)

E&C - \$489K, MEDAL - \$361K, Parsons - \$96K

Parsons Governmental Services
Pasadena, CA and Philadelphia, PA

Air Liquide Engineering
Champigny, France

MEDAL (Membrane Supplier)
Newport, DE

Delaware Research & Technology Center
Newark, DE



Project Objective / Target

■ PI-1 Bundle Optimization (Commercial Material)

- Improve performance by 30%

Four 12 inch bundles met performance target

■ PI-2 High Permeance CO₂ Fiber (Novel Material)

- 5X separation performance compared to PI-1

Fiber Performance target met

1 inch module preparation and testing in progress

■ 0.3 MWe Field Testing at NCCC

- Parametric testing in real flue gas
- >500 hours of steady state operation in field

Acceptance Testing of 2 skids is in progress

Compressor skid Acceptance testing in April

■ Techno-economic Analysis

- Evaluate potential to meet DOE target of \$40/tonne capture cost

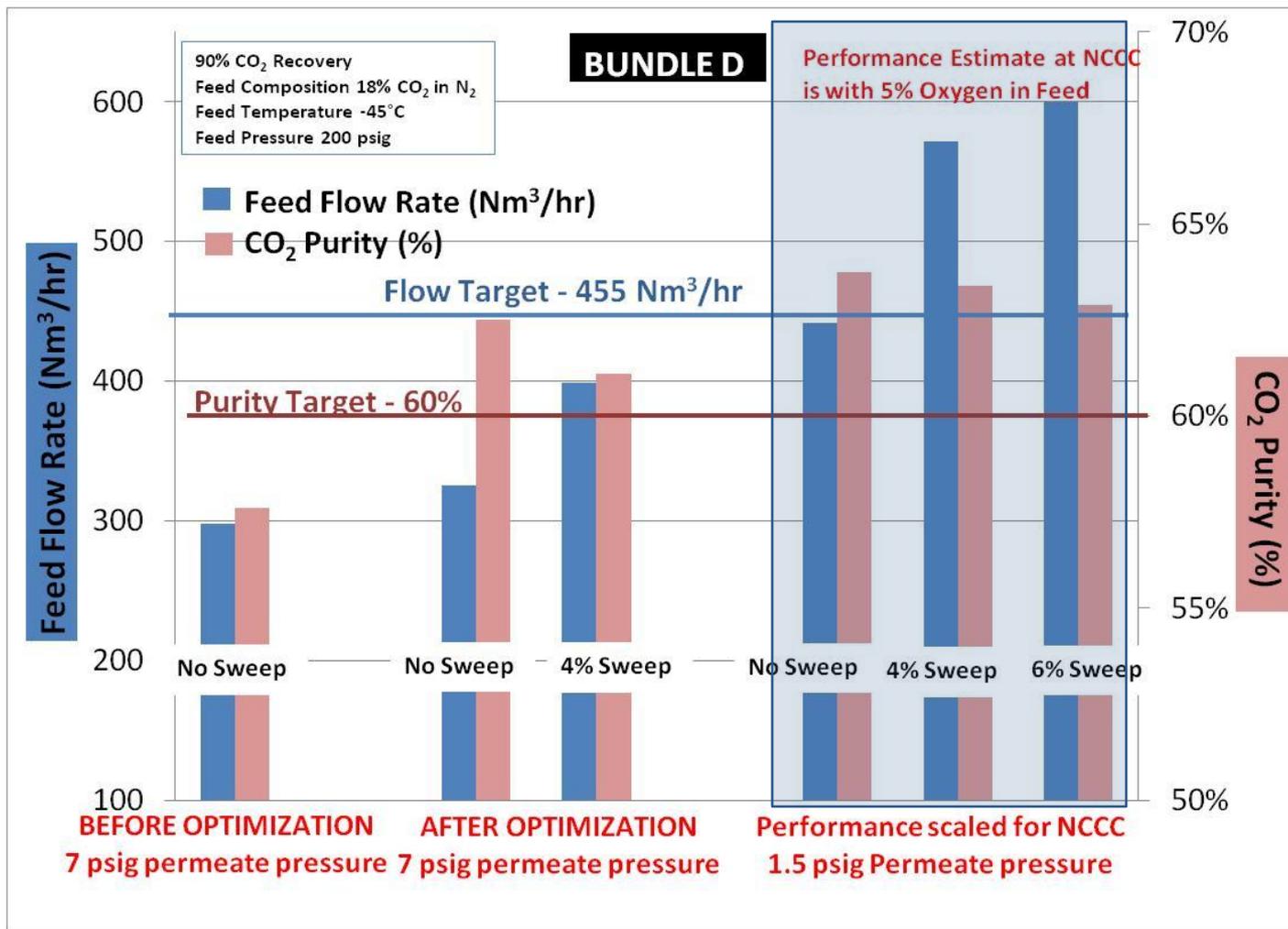
BP2 Objective

PI-1 Bundle Testing Summary

- PI-1 Material has been tested for >13,000 hours
 - Six 12 inch PI-1 commercial bundles tested in the current project ~5800 hours
 - Bundle C tested for >2400 hours
 - Two 6 inch PI-1 commercial bundles tested in previous project (DE-FE0004278)–7200 hours
- Following the modeling work and optimization 4/4 bundles (100%) have met or exceeded the performance target with the combination of experiment and simulation
 - Simulation is required because current bench scale skid (0.1 MWe) has the following limitations:
 - Feed flow rate 400 Nm³/hr due to the compressor size
 - Permeate pressure 7-8 psig due to the recycle loop
- Process Performance is scaled to NCCC conditions (1.5 psig permeate pressure and higher flow rate)
 - Feed flow capacity at NCCC~1000 Nm³/hr (0.3 MWe)
 - Blower added on the permeate to operate at 1.5 psig permeate pressure



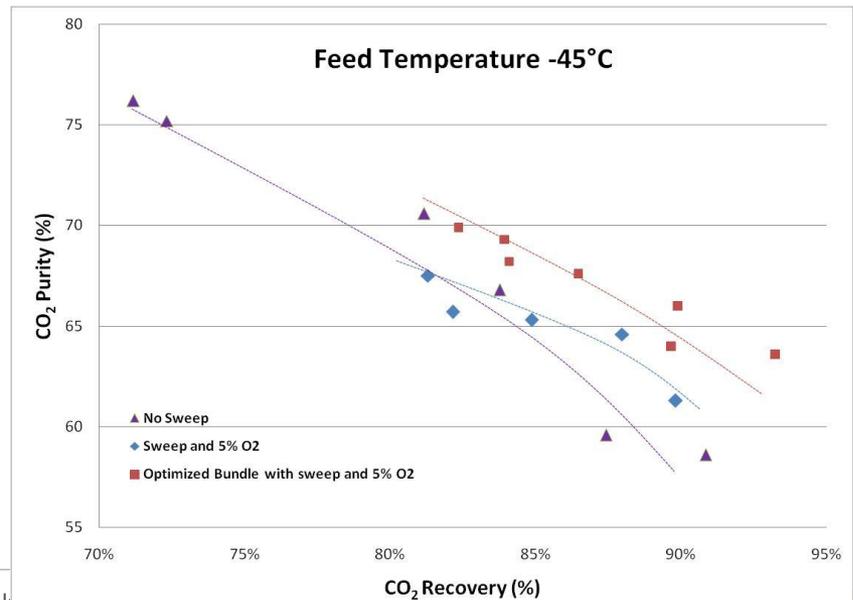
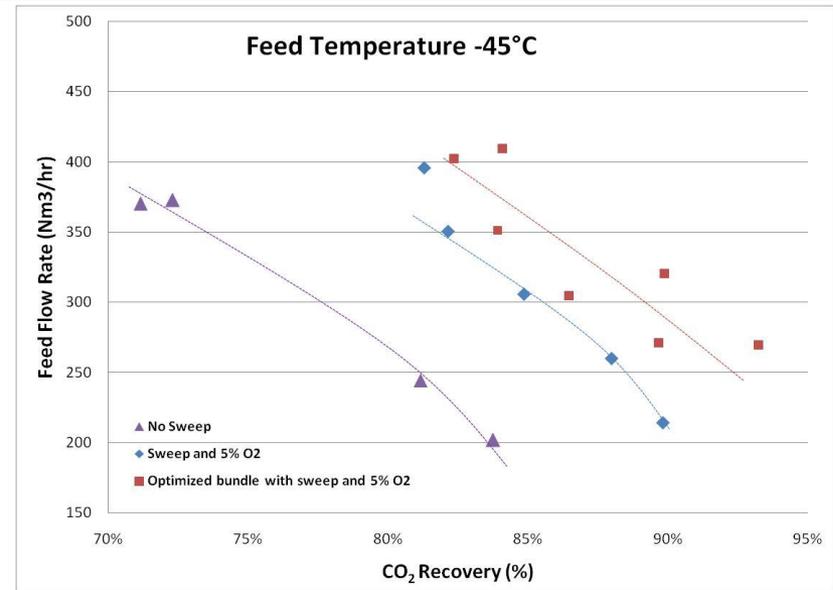
90% CO₂ Capture Data & Performance scaled for NCCC



Combination of experiments and simulations show that target Bundle Productivity and CO₂ purity can be achieved at 90% CO₂ recovery with optimized 12 inch MEDAL bundles

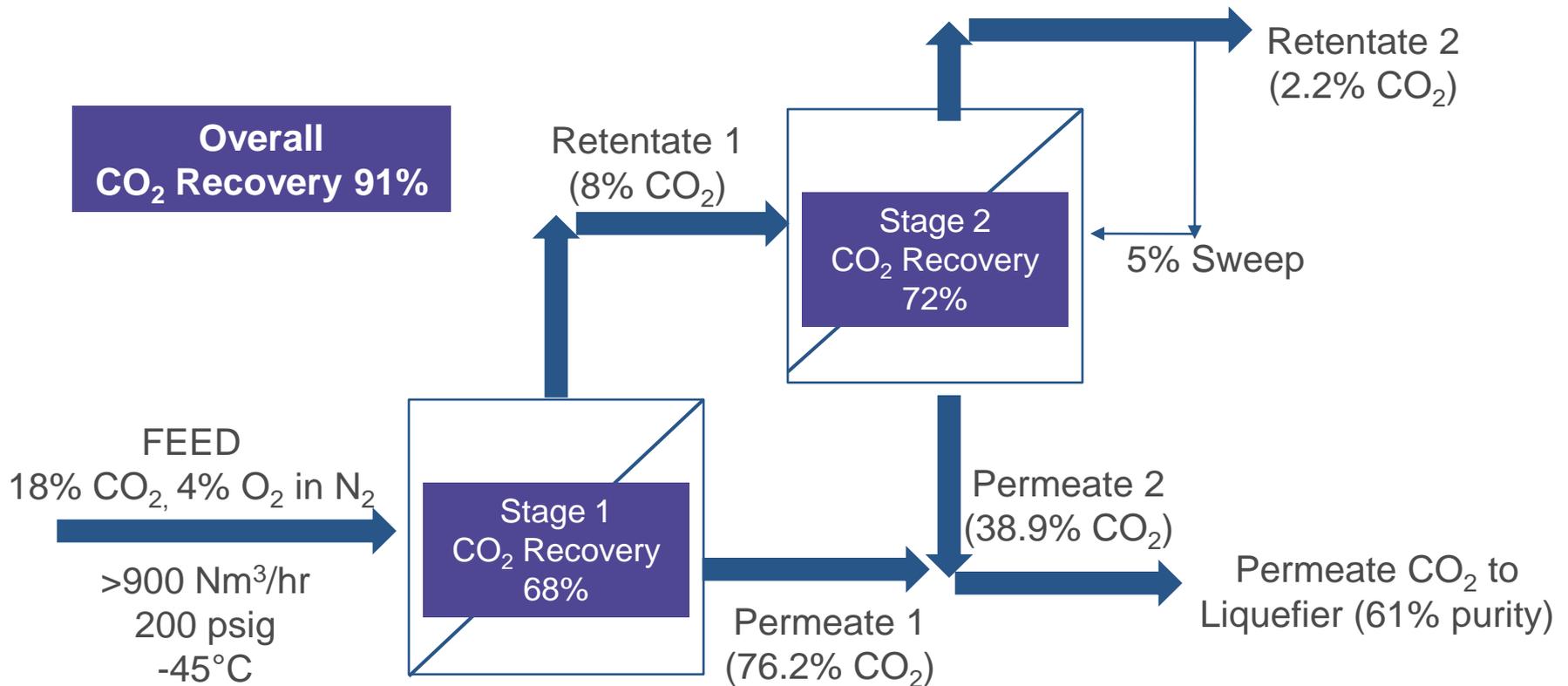
2 Stage Configuration

- >2X Bundle productivity can be achieved with 2 stage configuration
 - Total number of bundles for commercial solution is reduced
- 2 stage configuration in series is proposed for NCCC testing to operate each stage at lower stage cut (65-70% CO₂ recovery) for overall 90% recovery
- Validation testing of 2 stage configuration was completed in 0.1 MWe bench scale skid



0.1 MWe Bench scale test for 2 stage configuration

- Bundle E tested at simulated conditions in 2 stage configuration (Different feed composition) using 0.1 MWe Bench scale skid
 - 80-95% CO₂ Recovery range
- Experimental results used to calculate performance estimate at NCCC



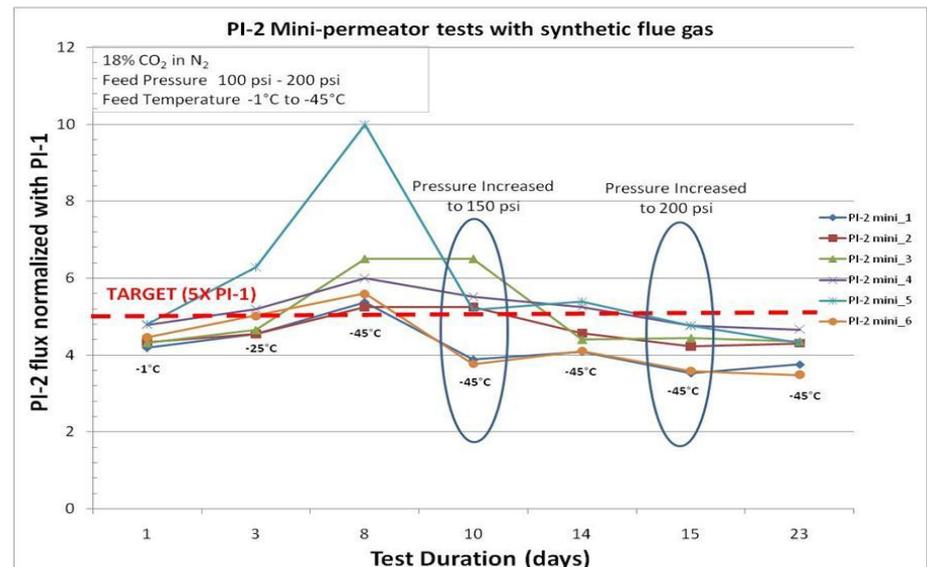
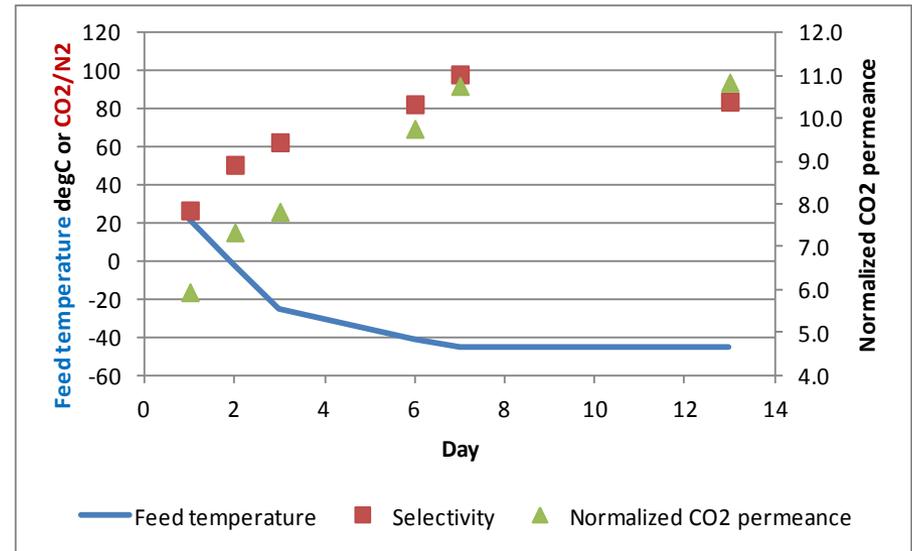
>2X Bundle productivity can be achieved with 2 stage configuration
Target : 450 Nm³/hr/Bundle

PI-2 Mini-Permeator test

- CO₂ flux is >5X compared to PI-1 material
- Increase in membrane separation performance at lower temperature consistent to PI-1

**Fiber Performance target has been met.
Passed Mechanical integrity test on
shell feed mini-permeators**

- 6 shell feed mini-permeators tested for >28 days passed mechanical integrity test
- Verified epoxy fiber adhesion is not an issue
- CO₂/N₂ selectivity >100



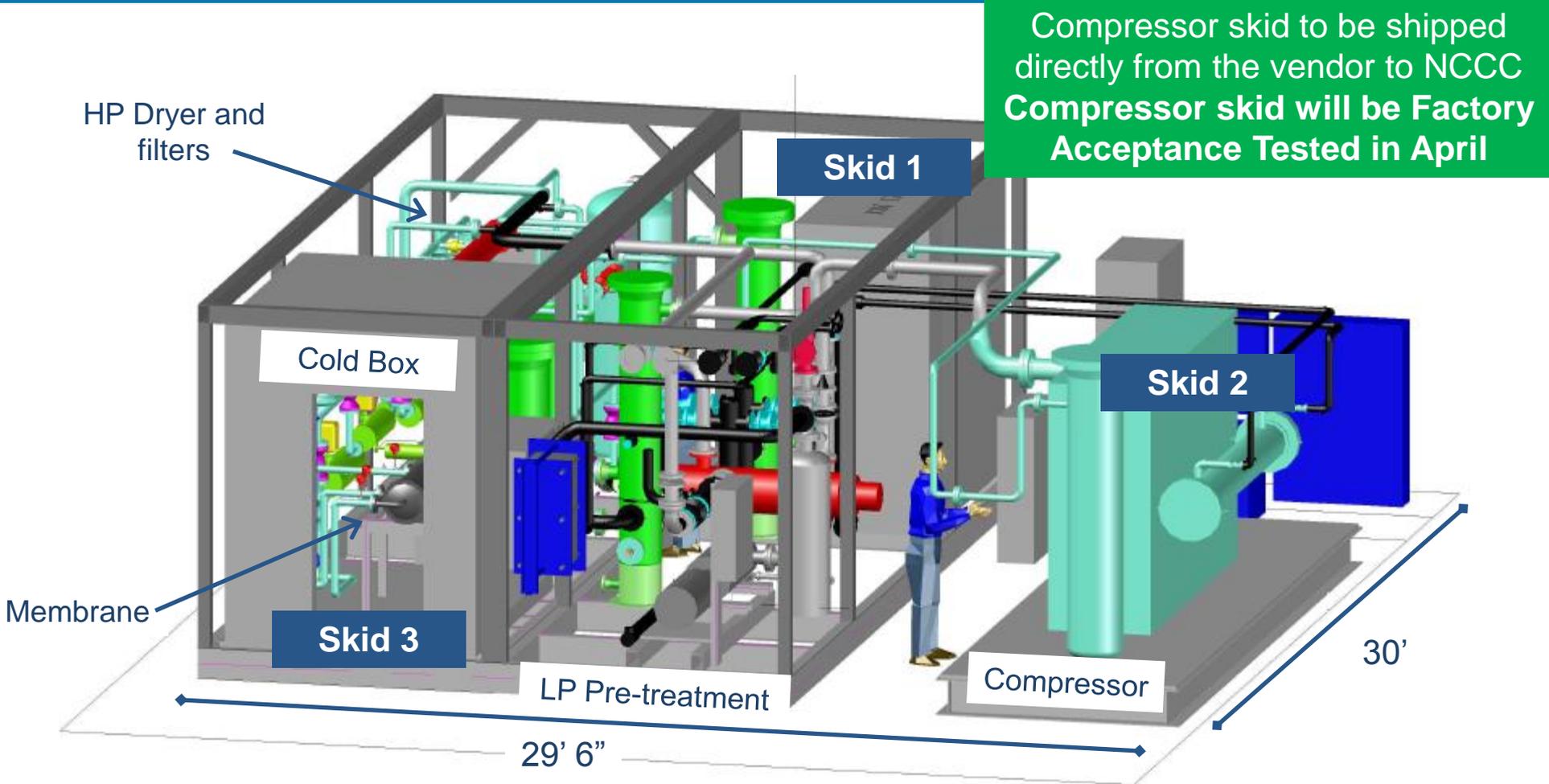
1 inch PI-2 Permeator Testing

- MEDAL commercial 1 inch bundle design is used to prepare PI-2 permeators
- 1 inch PI-2 permeator testing under way
- Further testing is continuing to improve the techniques for making 1 inch PI-2 Bundles
- We anticipate that the performance of 1 inch permeator will warrant further testing at NCCC

PI-2 1 inch permeator testing using synthetic flue gas shows initial promising results



0.3 MWe Field Testing at NCCC



Process equipment installation is complete on 2 skids (Pre-treatment and membrane skid) except the permeate blower. Acceptance testing and control programming is in progress.

0.3 MWe Field Test Unit Design and Construction

- Process equipment installation completed except permeate Blower
 - Pressure test on Pre-treatment Skid witnessed by AL: **PASS**
 - Pressure test on Membrane Skid witnessed by AL : **PASS**
- Acceptance testing by AL started (P&ID walkthrough, point to point check, loop testing)
 - Permeate Blower was FAT March 6th
 - Minor components (8 valves, 2 PRV's) will be received and installed in 1-2 weeks
 - Insulation of vessels and pipings will follow (2-3 days)



0.3 MWe Field Test Unit Design and Construction

- Electrical installation is completed - Acceptance testing on electrical equipment started Feb 15, 2015
- Controls/automation
 - HMI screens prepared and PLC code written - HMI and PLC started
- Few minor components will be received and installed in 1-2 weeks
- Control programming will be completed in March 2015

AL skids will be acceptance tested and ready to ship in April 2014



No cost extension request

- **Task 4 &5** - 1 inch PI-2 permeator Preparation & Testing – Optimization of fabrication techniques for 1 inch PI-2 permeator and testing using synthetic flue gas at DRTC (Q1 & Q2 BP2)
- **Task 6** – Acceptance Testing of skids (Q1, BP2)

**Extension request does not impact overall
Budget and Schedule**



Budget Status

- Cumulative Spending Q5 - \$2.5MM
- Projected Spending Q6 - \$700,000 to \$1MM
- **Carry Over in BP2 - \$600,000 to \$900,000**
 - Pending invoices from vendors and project partners
 - Will be Invoiced in Q1 or Q2 of BP2

	Q1		Q2		Q3		Q4		Q5		Q6	
	10/1/13 - 12/31/13		1/1/14 - 3/31/14		4/1/14 - 6/30/14		07/1/14 - 09/30/14		10/1/14 - 12/31/14		1/1/15 - 03/31/15	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q5	Cumulative Total	Q6	Cumulative Total
Baseline Cost Plan												
Federal Share	146970	146970	802819	949789	787876	1737665	808864	2546529	469793	3016321	353207	3369528
Non-Federal Share	36743	36743	200705	237447	196969	434416	202216	636632	117448	754080	88302	842382
Total Planned	183713	183713	1003523	1187236	984845	2172081	1011080	3183161	587241	3770402	441508	4211910
Actual Incurred Cost												
Federal Share	0	0	145509	145509	100205	245714	496603	742317	1187464	1929781		
Non-Federal Share	0	0	248309	248309	214293	462602	124151	586753	0	586753		
Total Incurred Cost	0	0	393818	393818	314498	708316	620754	1329069	1187464	2516534		
Variance												
Federal Share	146970	146970	657310	804280	687671	1491951	312261	1804212	-717672	1086540		
Non-Federal Share	36743	36743	-47604	-10862	-17324	-28186	78065	49880	117448	167328		
Total Variance	183713	183713	609705	793418	670347	1463765	390326	1854092	-600224	1253868		



Success Criteria List

Budget Period	Success Criteria	Accomplishment	Percent Complete	Projected Completion end of BP1
Budget Period 1 (Oct 2013 to March 2015)	A 12 inch PI-1 membrane bundle configuration capable of 90% CO ₂ recovery from a 455 Nm ³ /hr simulated flue gas feed containing 18% CO ₂ at 16 bar pressure with a permeate composition greater than 60% CO ₂ . This represents a 30% increase in membrane bundle capacity compared to the present performance of 350 Nm ³ /hr feed / bundle at the same operating conditions.	Four 12 inch Bundles met the performance target with 0.1 MWe Bench scale test using simulated flue gas with the combination of simulation and experiments. More than 30% improvement in bundle productivity was noticed with the addition of sweep and optimization of bundles.	100%	100%
	A 12 inch equivalent PI-2 membrane bundle (1-4 inch in actual diameter) capable of 90% CO ₂ recovery with a projected 5X simulated flue gas feed flow relative to PI-1 containing 18% CO ₂ at 16 bar pressure and greater than 60% CO ₂	PI-2 fiber has met the performance target with >5X flux compared to PI-1. Shell feed minis have passed the mechanical integrity test. Further test are continuing with 1 inch PI-2 permeator using MEDAL design.	75%	80% (100% projected completion in Q2 BP2)
	A completed specification list for the CO ₂ membrane field test unit at 0.3 MWe detailing major equipment sizing with mass and energy balances that serves as a blueprint for engineering design. The specification list will demonstrate that the proposed design is within the approved budget. The design will be submitted to NETL and NCCC for review of the CO ₂ membrane field test unit at 0.3 MWe.	Specification list for the CO ₂ membrane field test unit is complete. The proposed design is within the approved budget and has been reviewed by NETL and NCCC.	100%	100%
	A final detailed engineering process design package including pre-treatment, compression and drying equipment upstream of the cold membrane bundle field test unit within the project budget (± 10% estimate)	Detailed drawings of most major equipment, line & valve sizing, electrical drawings, arrangement drawings are completed.	100%	100%
	Written confirmation from Southern Company Services (SCS) that the NCCC will be the host site for the location of the CO ₂ membrane field test unit and related equipment at 0.3 MWe during BP2. Confirmation is inclusive of the host utility agreement to provide accommodation of the proposed platform area, tie-ins with electrical and water utilities. Confirmation will include acceptance of the final field test unit design prior to fabrication.	Written Confirmation has been received from NCCC that they are willing to host the AL cold membrane technology and the design meets NCCC standard.	100%	100%
	High Permeance (PI-2) CO ₂ membrane hollow fiber bundle testing with simulated gas will be performed. Optimized CO ₂ membrane bundle(s) (PI-1 and PI-2) identifying the configuration(s) for field test unit will be provided. The configuration comparison will include a predicted performance comparison between the two membranes (PI-1 and PI-2).	Optimized PI-1 bundles have been tested and >30% increase in performance validated.PI-2 permeators have been tested with increased performance..1 inch PI-2 permeator fabrication technique is under investigation.	75%	80% (100% projected completion in Q2 BP2)

Milestone Log

Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Milestone 1. Complete Safety & Hazard Review for NCCC field test unit with completed P&ID and controls strategy complying AL, NETL and NCCC safety regulations	4/30/2014	HAZOP 03/19/14 Second Review 10/21/2014	NCCC has provided letter of their participation in the HAZOP and AL design meeting NCCC standards "as reviewed in October, 2014"	HAZOP was conducted at DRTC with participation from AL R&D, E&C and NCCC experts in March 2014. A second round of review was conducted at NCCC site.
Milestone 2. Complete PI-1 Optimization test with 30% improvement in Bundle capacity for a 12 inch bundle to reach target of 455 Nm ³ /hr with 90% CO ₂ Capture and >60% CO ₂ in the permeate stream	12/31/2014	11/20/2014	Four 12 inch bundles have met the performance target with 30% improvement in bundle capacity using sweep and optimization techniques from CFD.	Combination of experiment and simulations show that the target productivity is met.
Milestone 3. – Complete PI-2 High Permeance CO ₂ fiber bundle fabrication & testing with projected 12 inch performance to reach target of 2000 Nm ³ /hr with 90% CO ₂ capture and >60% CO ₂ in the permeate stream	3/30/2015	Projected completion in Q2 BP2		PI-2 fiber has met the performance target with >5X flux compared to PI-1. Recent study suggest higher mechanical integrity for PI-2 fibers with 100% survival rate for shell feed mini-permeators. Further investigation on fabrication techniques are on-going to manufacture 1 inch PI-2 permeator.
Milestone 4. Complete design, procurement, detailed engineering and fabrication of 0.3 MWe field test unit with component acceptance tests to check for functionality	3/31/2015	Projected completion in Q1 BP2		All equipments have been ordered with majority of them received and installed. Detailed engineering is complete. Skid fabrication is 90% complete and Acceptance testing is in progress. Acceptance testing of pre-treatment, membrane and Compressor skid will be completed in Q1 BP2.

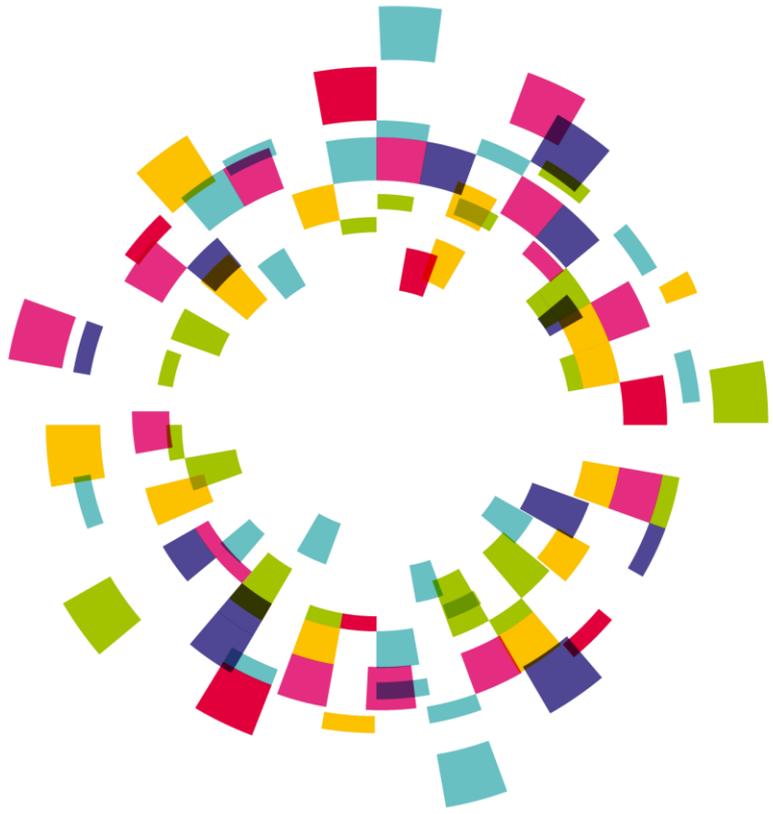


Scope for Budget Period 2 & Authorization to Proceed

- 0.3 MWe Field testing at NCCC
- TEA and EH&S analysis for CO₂ capture using cold membrane technology
- Multi-bundle field test design
- Extension Request on PI-2 permeator fabrication and testing

DOE Approval needed to proceed to BP2





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