CO2 CAPTURE BY SUB-AMBIENT MEMBRANE OPERATION

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Air Liquide: Key information

A world leader in industrial and medical gases

> 42,000 employees

~ $ 15 billion sales (2009)

Proposed new technology leverages AL strengths

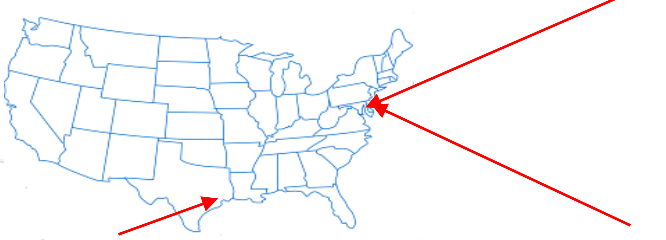
- **MEDAL – Established membrane manufacturer for N_2, H_2 and CO_2 applications**
- **Air Liquide core expertise in gas separation, cryogenics and gas handling**
- **Strong program related to coal oxy-combustion**

CO_2 Capture by Sub-Ambient Membrane Operation

- **Bench scale test of CO_2 separation using a hollow fiber membrane module at cryogenic conditions**

- **Funding Request:**
  - **DOE: 1.266 M$; Cost share: 0.32 M$**

- **Duration – 24 months**



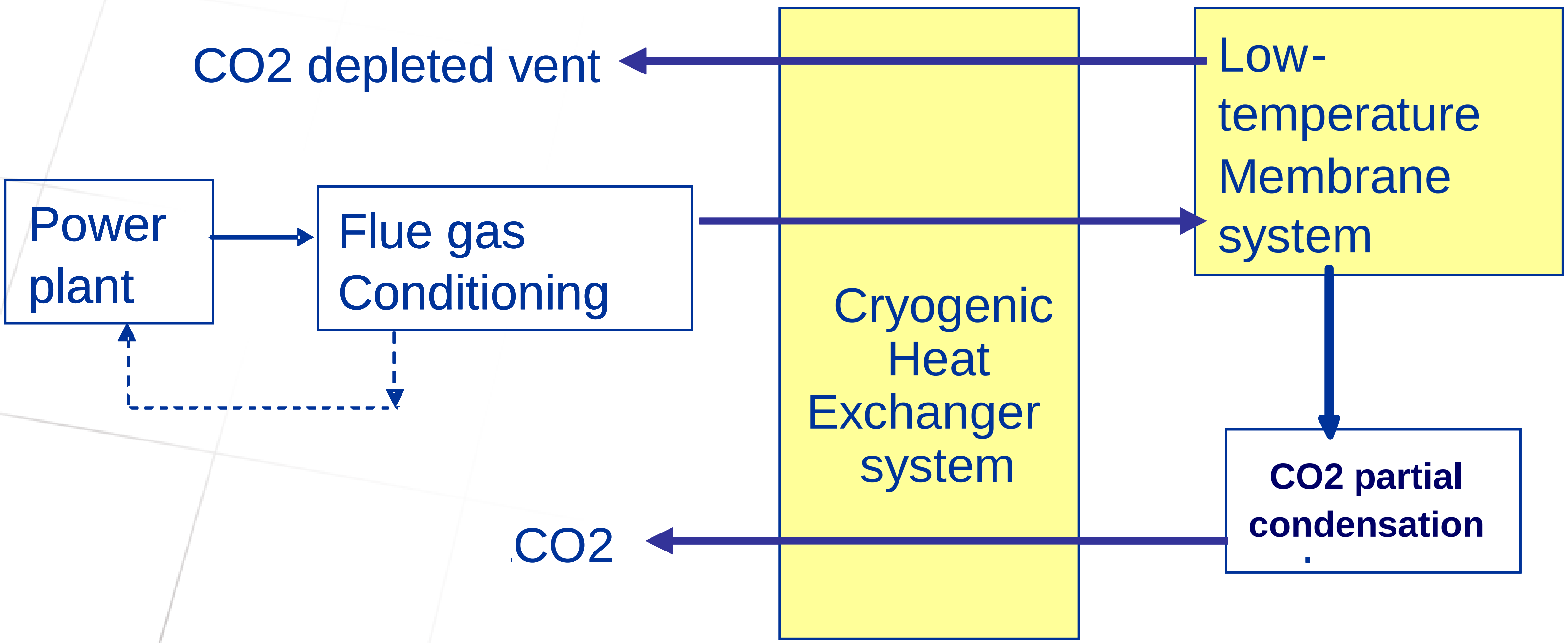
Air Liquide Advanced Technologies US – MEDAL (membrane manufacturing)

American Air Liquide Delaware Research & Technology Center (Separations, Combustion, Analysis..)

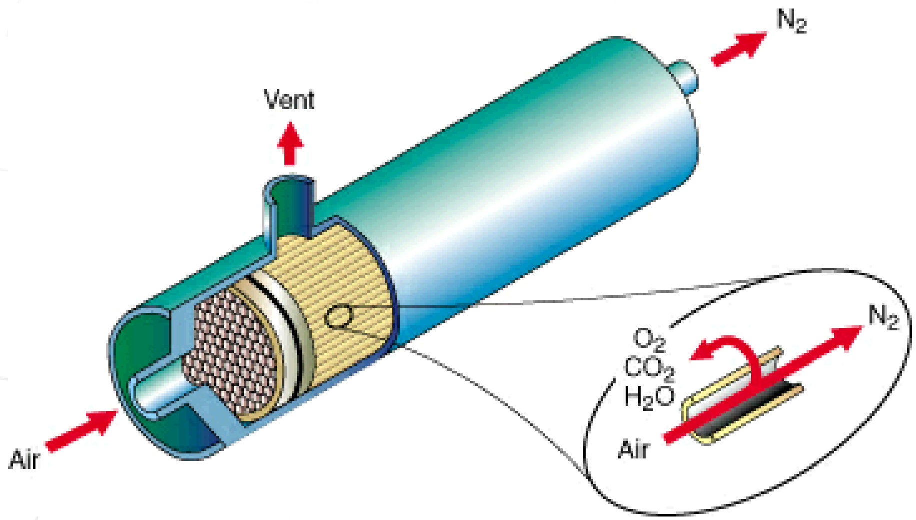
Air Liquide America Process and Construction (Engineering process design)

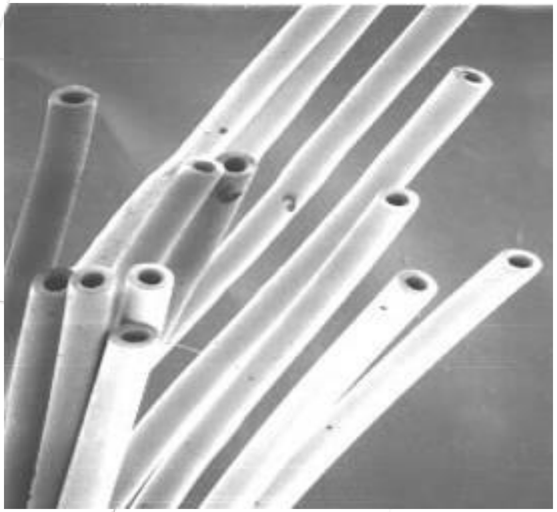
Cold Membrane Concept

- Pre-concentration of CO_2 by **highly selective cold membrane** before CPU Liquefier
- **Energy integration** between membrane / liquefier through heat exchange



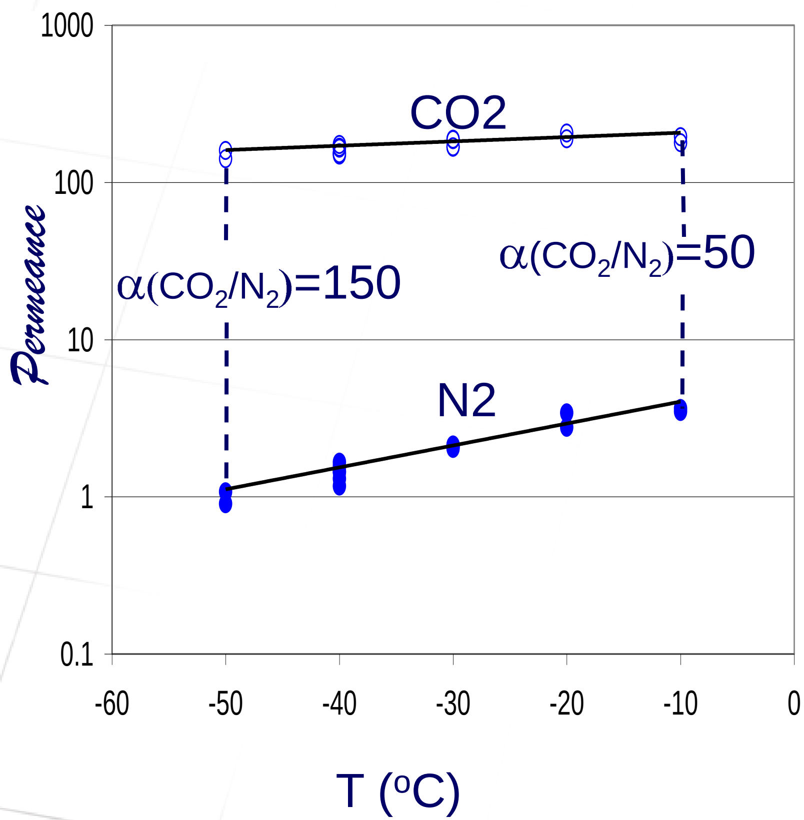
Proposal based on existing AL membrane

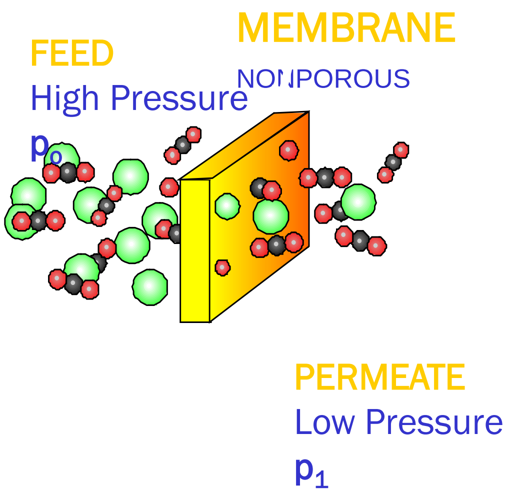


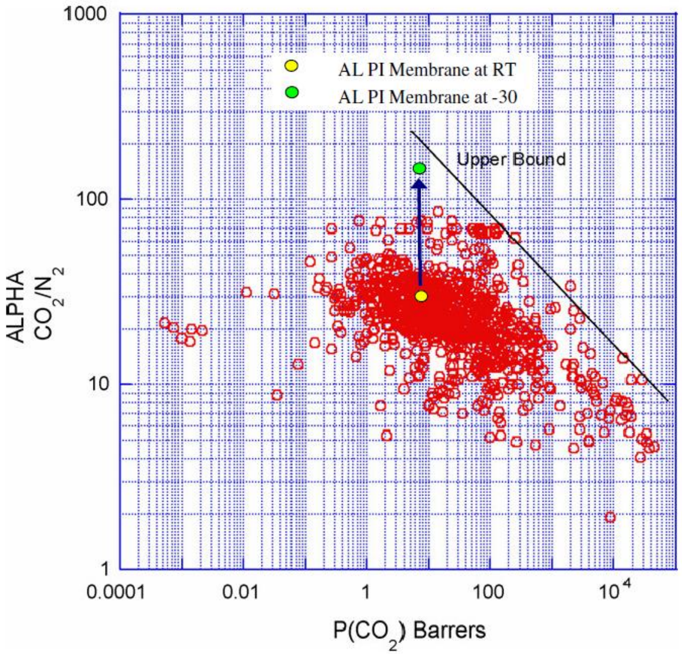


Hollow fiber membrane provides most cost effective solution for large gas separation applications

Low temperature membrane performance

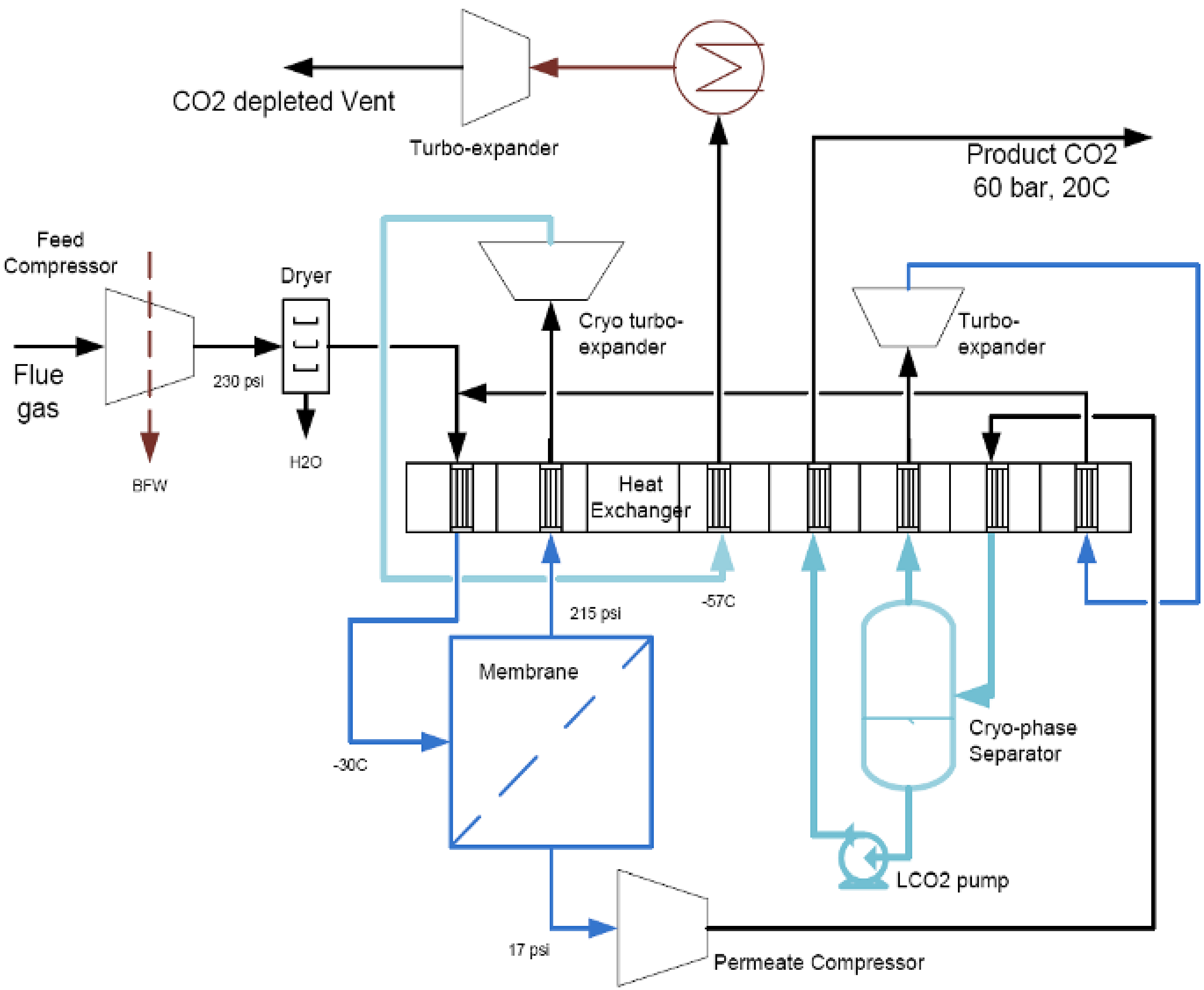






Existing AL Membrane operated at < -10C has unique high CO2 permeance and selectivity.

Hybrid membrane + CPU configuration



Hybrid process can meet DOE criteria

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		Air Fired PC		
Cases (Refer to Report DOE/NETL 2007-1291)		1	3	**Current Proposal**
		No CO2 Removal	Post Combuston CO2 Removal Econamine™	**Post Comb. CO_2 Removal Cryo Membrane Process**
Coal Feed Rate	**[lb/hr]**	408,404	568,639	568,639
Flue Gas Flow Rate*	**[Nm3/hr]**	1,655,946	2,313,327	2,313,327
CO_2 Emitted	**[Nm3/hr]**	224,050	31,154	31,154
Turbine Cycle Net Power	**[KWe]**	580,200	661,100	807,838
Auxiliary Power	**[KWe]**	30,170	111,130	152,984
Net Plant Efficiency	**[%]**	39%	28%	34%
Net Plant Heat Rate	**[Btu/ KWh HHV]**	8,662	12,062	10,130
Net Power	**[MWe]**	550,030	549,970	654,854
Total Plant Cost [TPC] **w/o** T, S&M	**[k$]**	868,230	1,570,207	1,316,544
LCOE **w/o** T,S&M	**[¢/kWhr]**	6.32	10.91	8.15
LCOE **w/** T,S&M	**[¢/kWhr]**	-	11.3	8.49
Increase in LCOE (w/o T, S&M)	**[%]**		**78.80**	**28.97**
Increase in LCOE (w/ T, S&M)	**[%]**		**78.80**	**34.29**

Expected development challenges

- Challenges specific to sub-ambient membrane operation
  - Module materials
  - Permeance-selectivity of commercial module
  - Long term module performance stability
- Integration of membrane process
  - Energy integration with CPU
  - Energy integration with power plant
    - Compression and Turbo-expansion schemes
    - Heat economizers and Exergy conservation
  - Large but feasible membrane area production
- Contaminant specific challenges
  - Acid gas (NOx, SO_2) separation
  - Compressor materials
  - Particulate removal
  - Hg
  - Water handling

Detailed Project objectives

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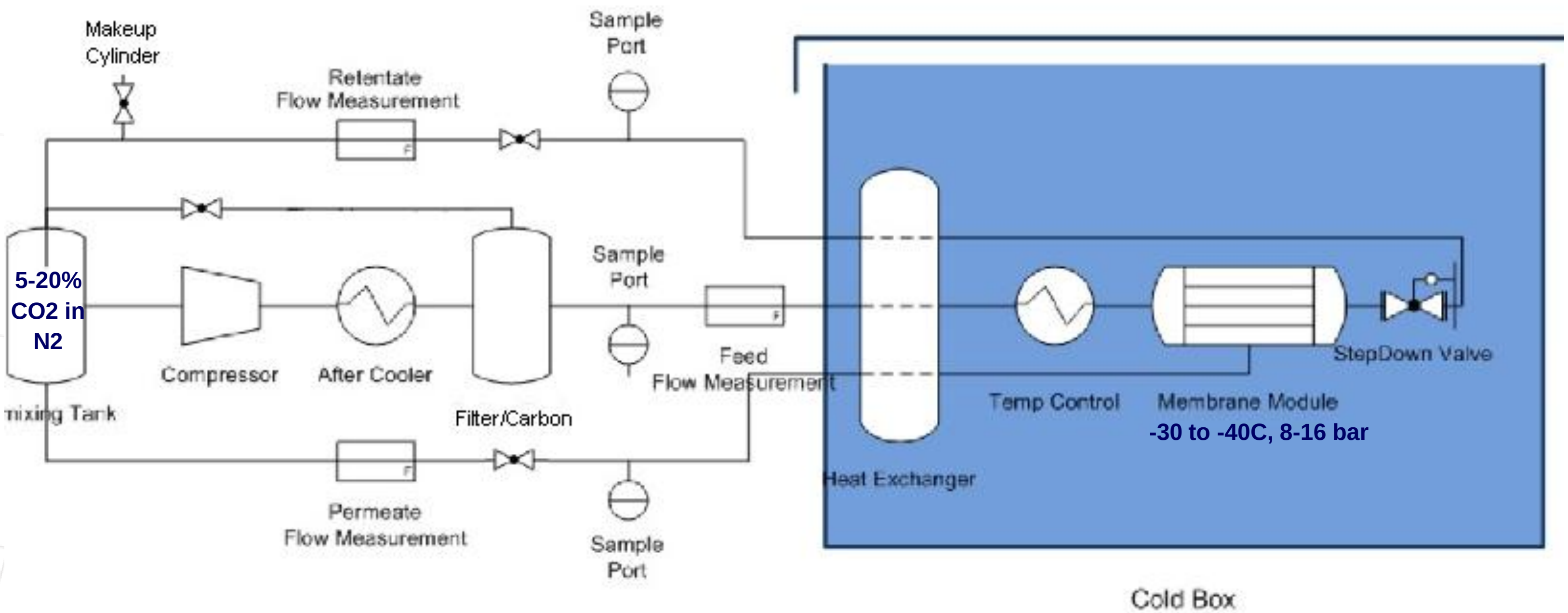
1. Demonstrate high selectivity / permeance performance with a commercial scale membrane module in a bench-scale test skid
2. Verify mechanical integrity of commercial scale membrane module structural components at sub-ambient temperatures.
3. Demonstrate long term operability of the sub-ambient temperature membrane skid
4. Evaluate effect of expected contaminant levels (SOx, NOx, water) on membrane performance (lab tests).
5. Refine process simulation for integrated process with flue gas conditioning and liquefier.
6. Design slip-stream-scale unit for possible field test

Cold membrane test skid



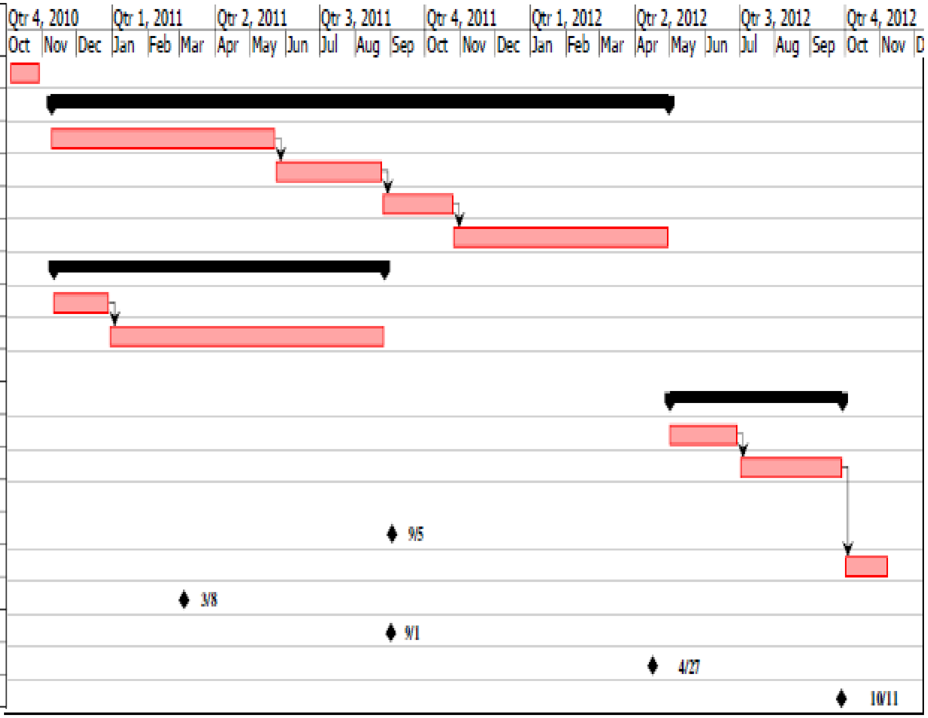
1. **Demonstrate high selectivity / permeance performance with a commercial membrane module in a bench-scale test skid.**
2. **Verify mechanical integrity of commercial membrane module structural components at sub-ambient temperatures.**
3. **Demonstrate long term operability of the sub-ambient temperature membrane skid without external source of refrigeration.**

Laboratory testing for acid gas separation

- Existing cold test system to be modified for acid gas testing using minipermeators
- Concentration analysis protocols to be validated

Project main tasks and timeline

	Name	Start	Finish
1	Project kick-off with DOE	10/1/10 5:00 PM	10/29/10 5:00 PM
2	**⊟TASK 1. Demonstrate Commercial...**	**11/9/10 8:00 AM**	**4/30/12 5:00 PM**
3	1.1. Design and Fabricate sub-ambi...	11/9/10 8:00 AM	5/23/11 5:00 PM
4	1.2. Mechanical integrity testing	5/24/11 8:00 AM	8/24/11 5:00 PM
5	1.3. Performance map of bundle	8/25/11 8:00 AM	10/25/11 5:00 PM
6	1.4. Long term operation test	10/26/11 8:00 AM	4/30/12 5:00 PM
7	**⊟TASK 2. Laboratory Scale Flue Ga...**	**11/11/10 8:00 AM**	**8/26/11 5:00 PM**
8	2.1. Lab scale equipment modification	11/11/10 8:00 AM	12/29/10 5:00 PM
9	2.2. SOx / NOx measurements	12/30/10 8:00 AM	8/26/11 5:00 PM
10	**⊟TASK 3. Sub-ambient Membrane/...**	**5/1/12 8:00 AM**	**9/28/12 5:00 PM**
11	3.1. Conceptual design of commerci...	5/1/12 8:00 AM	6/29/12 5:00 PM
12	3.2. Engineering Design for Slipstre...	7/2/12 8:00 AM	9/28/12 5:00 PM
13	Annual Review Go/no-go	9/1/11 5:00 PM	9/5/11 5:00 PM
14	Final Report / Review	10/1/12 8:00 AM	11/7/12 5:00 PM
15	Status report	3/4/11 4:00 PM	3/8/11 4:00 PM
16	Topical reports	9/1/11 8:00 AM	9/1/11 8:00 AM
17	Topical reports	4/16/12 8:00 AM	4/27/12 5:00 PM
18	Topical reports on Design	9/28/12 8:00 AM	10/11/12 5:00 PM



Task 1 : Demonstrate commercial scale bundle operation at sub-ambient temperature

Task 2 : Laboratory Scale Flue Gas Contaminant Testing

Task 3 : Sub-ambient Membrane/Cryogenic System Design

Project deliverables and path forward

- Validation of membrane module performance under sub-ambient conditions with synthetic (clean) gas (Task 1)
- Laboratory measurements of acid gas contaminant separation (Task 2)
- Engineering outputs (Task 3):
  - Technical & economic re-assessment of CO_2 capture process concept(s) with data from tasks 1 & 2
  - Design of slip-stream test system for field test (if appropriate)