

Supersonic Post-Combustion Inertial CO₂ Extraction System

Bench Scale Project Status Update

NETL-DOE 2014 Transformational Carbon Capture Technology
Workshop

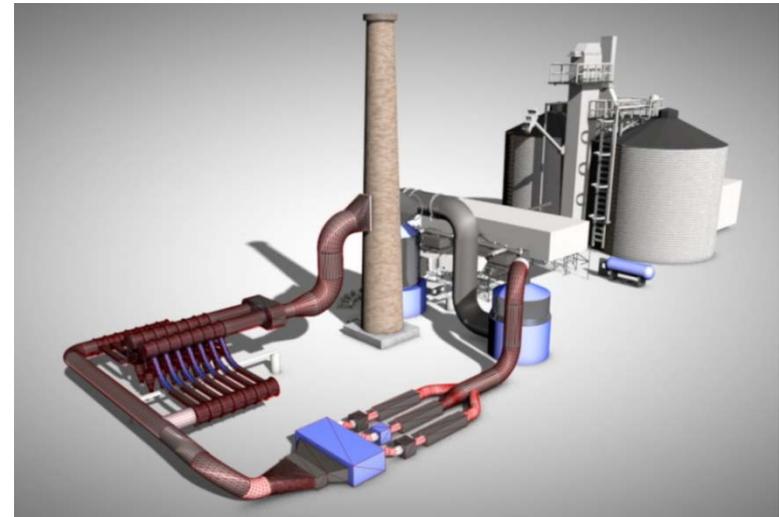
September 23, 2014

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- **Award DE-FE0013122**

- **Funding**

- NETL: \$ 2,999,951
- Cost Share: \$ 749,640
- Total: \$ 3,749,591

- **Project Performance Dates**

- 1 Oct 2013 - 30 Sep 2016

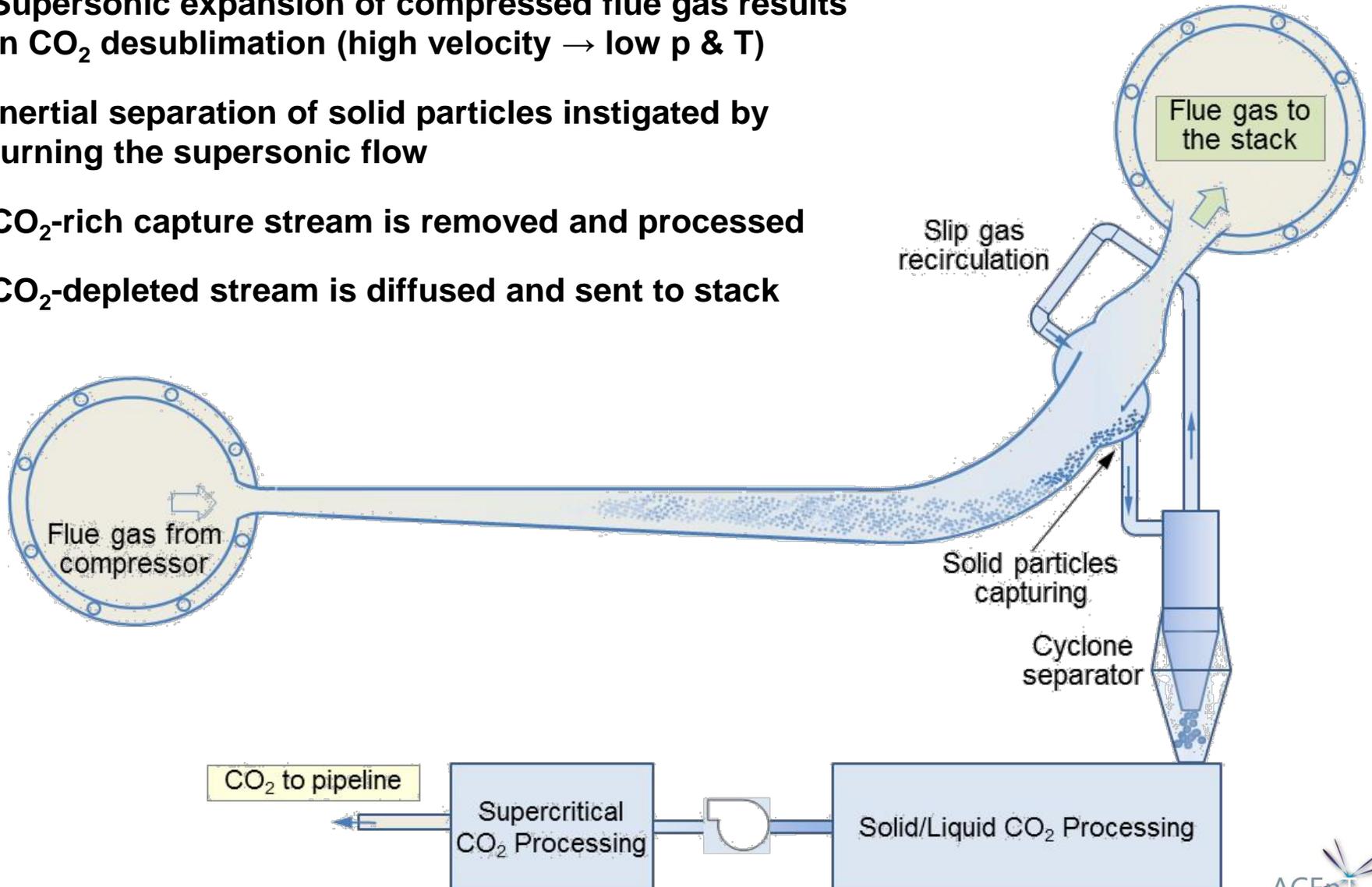
- **Project Participants**

- ATK & ACENT Laboratories
- Ohio State University
- EPRI and WorleyParsons
- NYSERDA and NYSDE

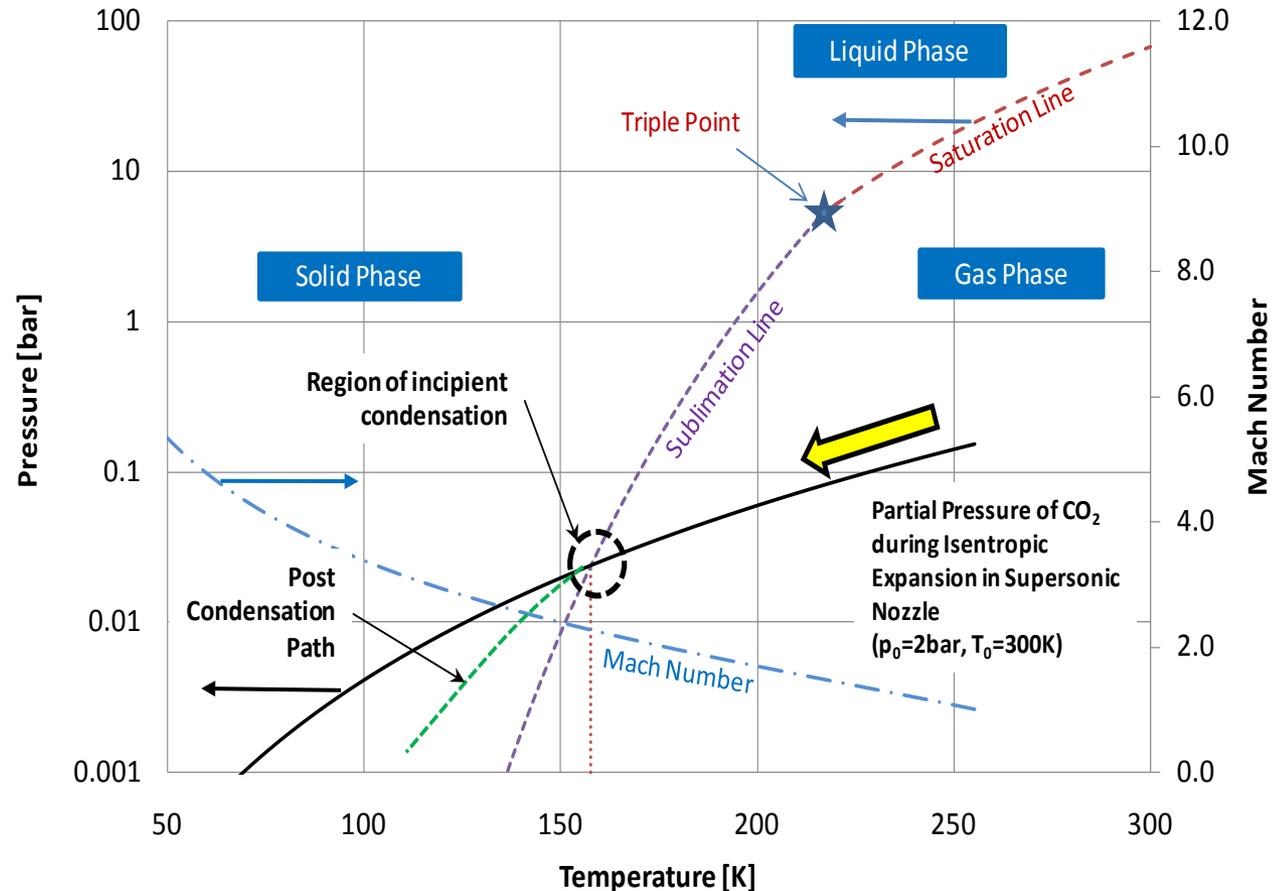
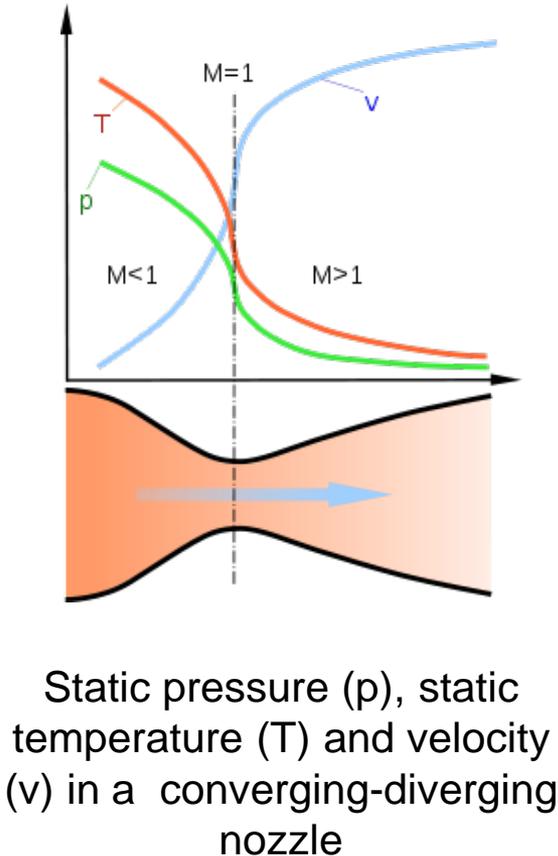
- **Project Objectives**

- Demonstrate inertial CO₂ extraction system at bench scale
- Develop approaches to obtain condensed CO₂ particle size required for migration
- Demonstrate pressure recovery efficiency of system consistent with economic goals
- Demonstrate CO₂ capture efficiency

- Supersonic expansion of compressed flue gas results in CO₂ desublimation (high velocity → low p & T)
- Inertial separation of solid particles instigated by turning the supersonic flow
- CO₂-rich capture stream is removed and processed
- CO₂-depleted stream is diffused and sent to stack



Isentropic Expansion of 14mol% CO₂ in N₂ Relative to Phase Diagram of CO₂



Low static pressure and temperature in supersonic nozzle causes CO₂ to precipitate as a solid – need to remove before diffusing back to low speed

Key Advantages and Challenges



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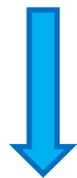
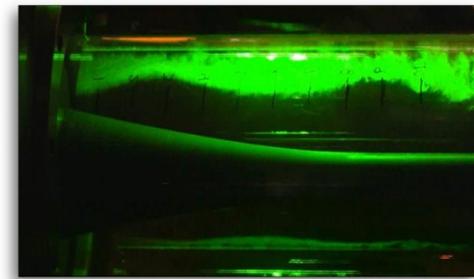
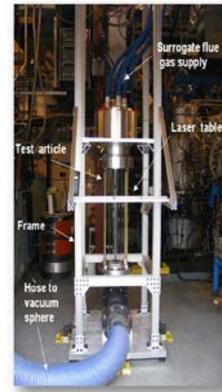
Advantages	Challenges
No moving parts, chemicals/additives or consumable media	Maximization of CO ₂ particle size with limited residence time
Inexpensive construction (sheet metal, concrete)	Minimization of “slip gas” removed with solid CO ₂
Small footprint (current bench scale test article is 250kW, 3” x 24” x 96”)	CO ₂ purity (all condensable material will be removed with CO ₂)
“Cold sink” availability in solid CO ₂	Solid CO ₂ processing
Costs primarily driven by flue gas compression	Optimization of flowpath pressure recovery

Summary of test activity under ARPA-e IMPACCT

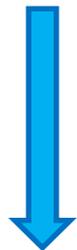
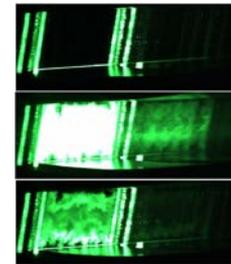
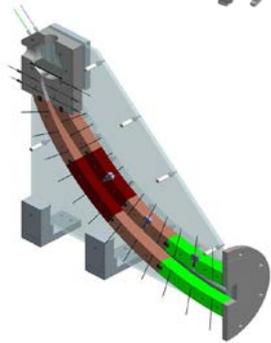


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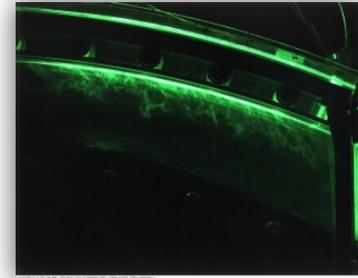
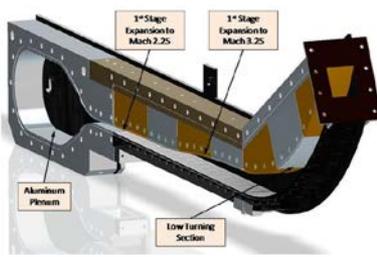
Gen1a and 1b (swirl)



Gen2 (2D)



Gen3 (2D - long)



Principal conclusion of this effort was that CO₂ particles >2.5μm are required for efficient operation - need to control particle size generated



- **Year 1**

- Lab-scale tests (OSU) to develop understanding of factors controlling particle size and methods to increase
- Bench scale tests at ATK to demonstrate capture efficiency and diffusion with surrogate CO₂ injection (liquid throttle of CO₂ to produce controlled particle size)
- Success criteria: Demonstrate 50% capture, show path to pressure recovery required

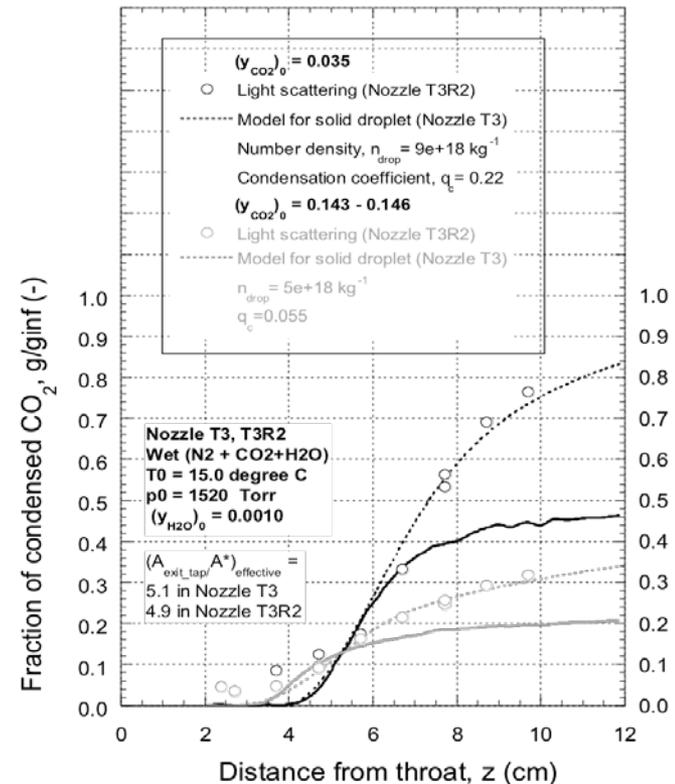
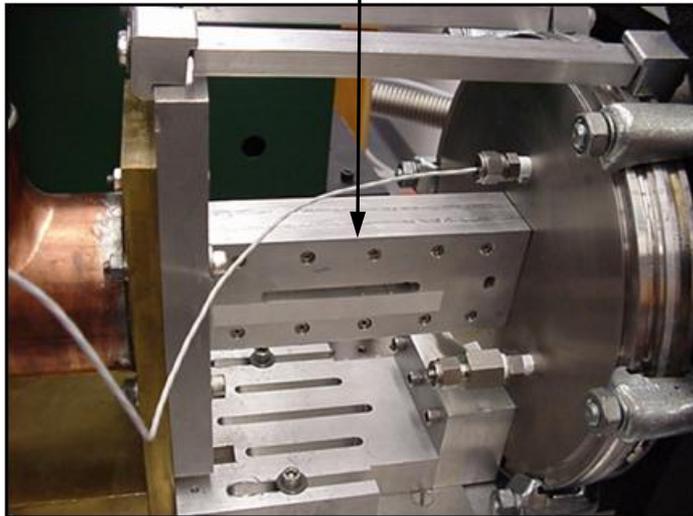
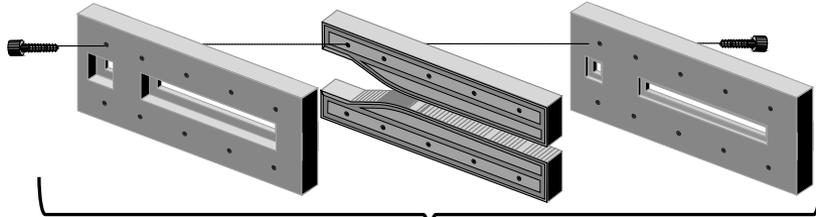
- **Year 2**

- Integrate methods to increase particle size in bench scale test article
- Test with surrogate flue gas (Air + CO₂ + H₂O)
- Success criteria: Demonstrate migration of 80% of CO₂ to 20% of duct height pressure recovery

- **Year 3**

- Integrated bench-scale testing with capture + diffuser
- Success criteria: 75% capture with path to 90%, path to full scale pressure recovery

- Tests ongoing in OSU supersonic aerosol facility to gain better understanding of nucleation process, condensation rates, and particle size behavior

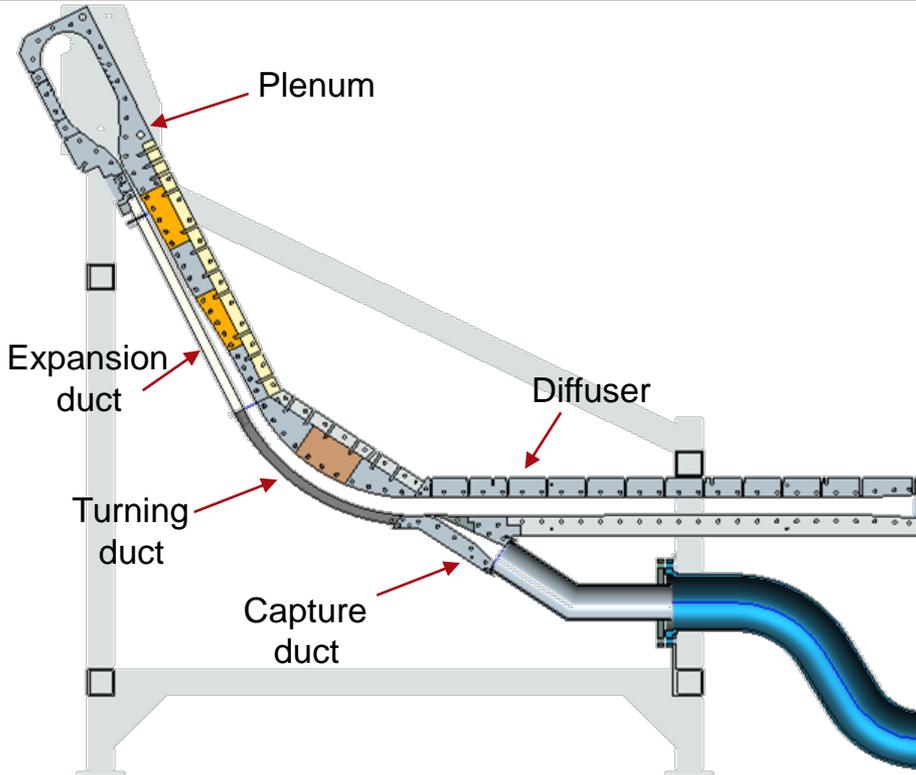


Particle size diagnostic has been demonstrated and calibrated – will be moving into particle growth testing next

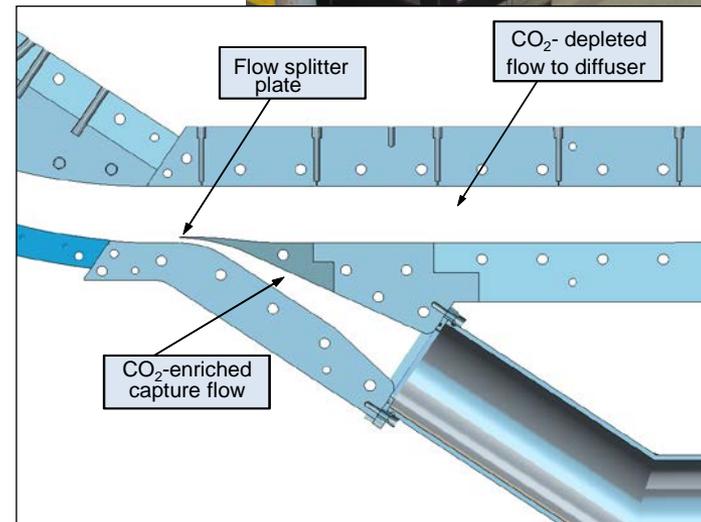
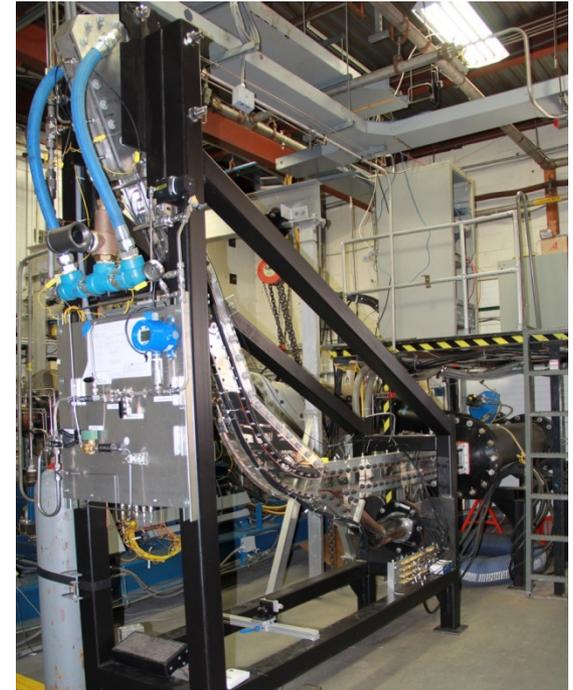
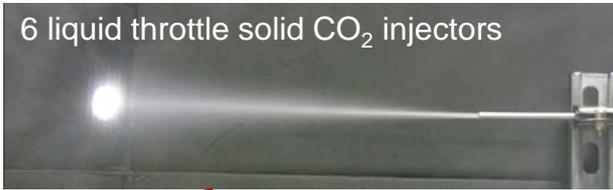
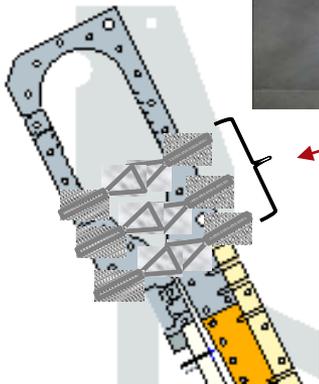
Current Bench Scale Test Arrangement (250kW)



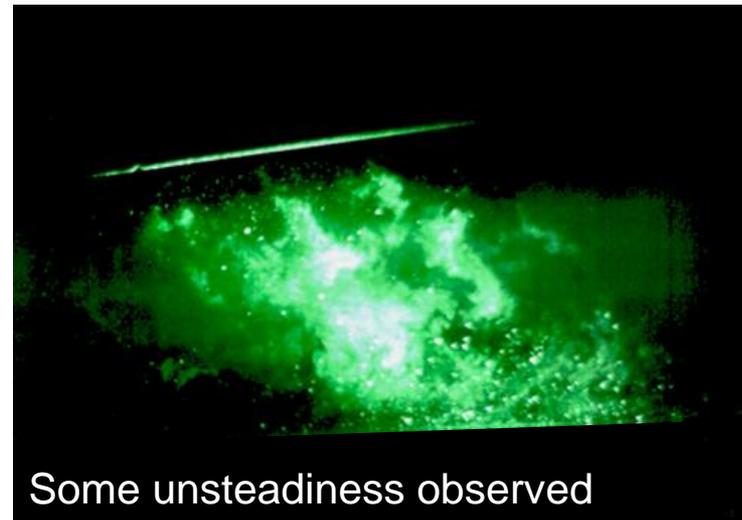
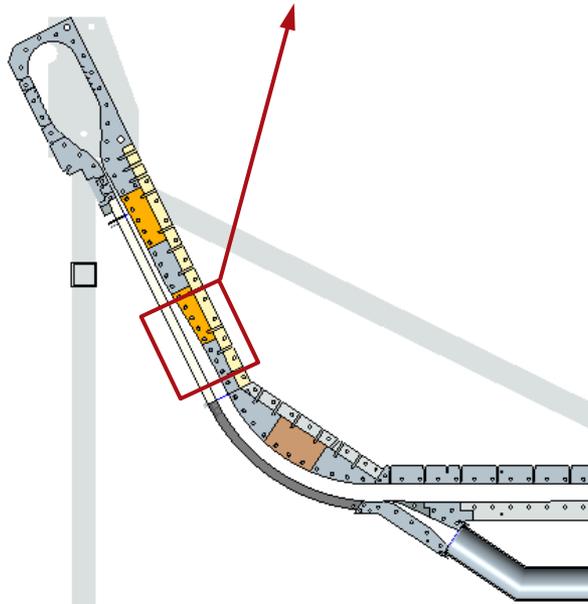
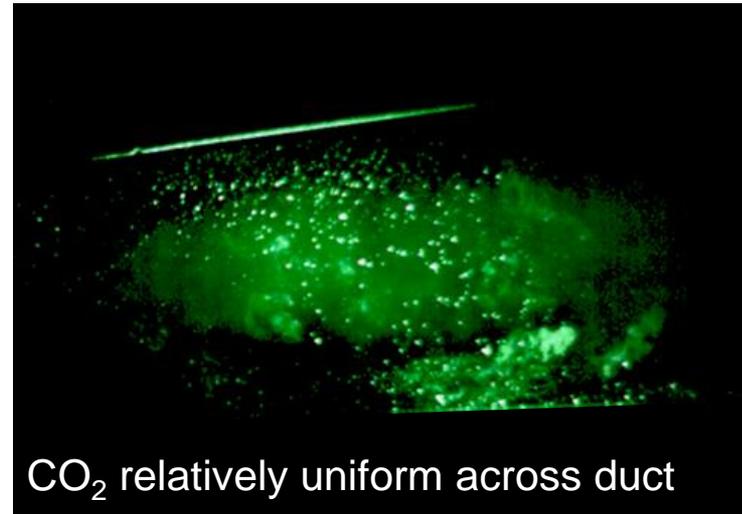
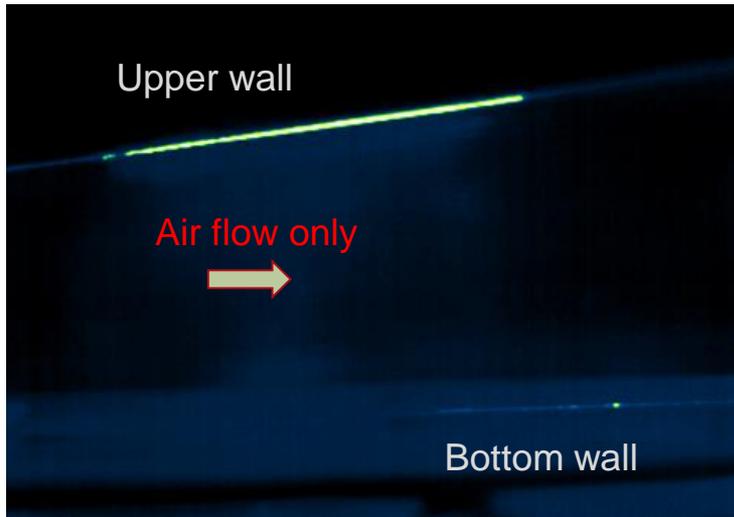
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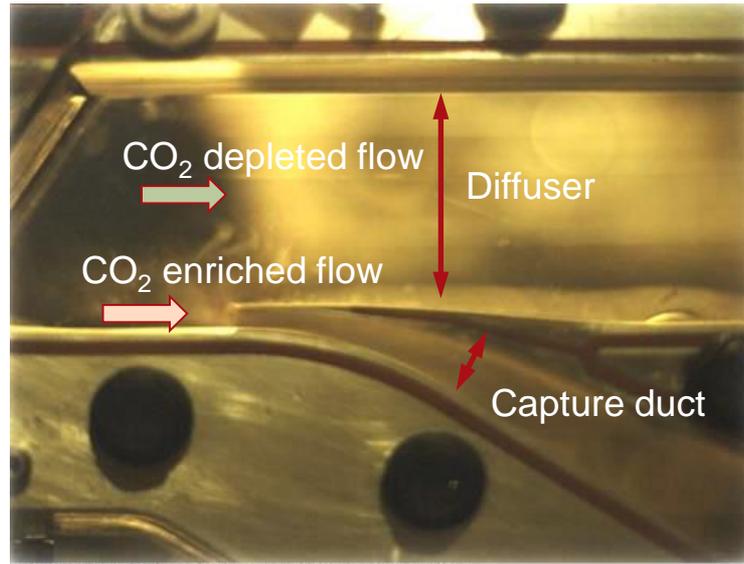
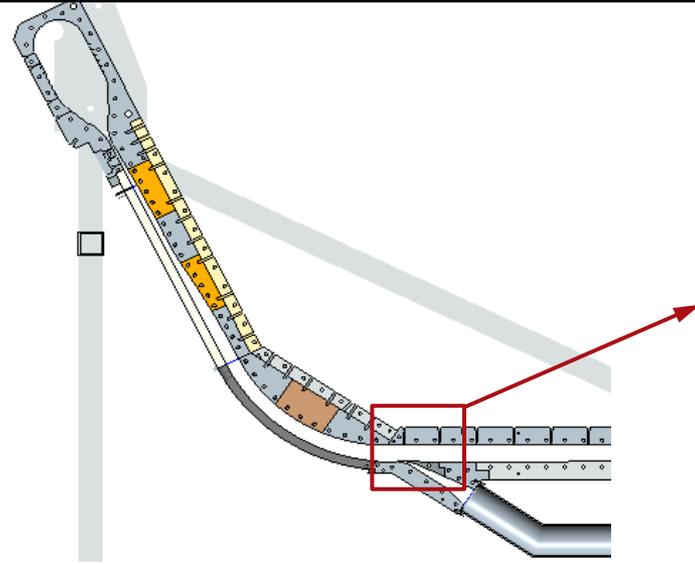
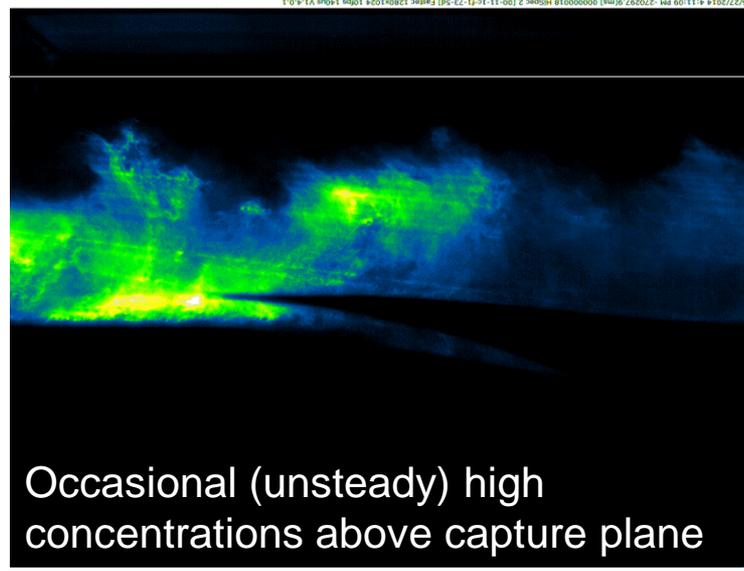
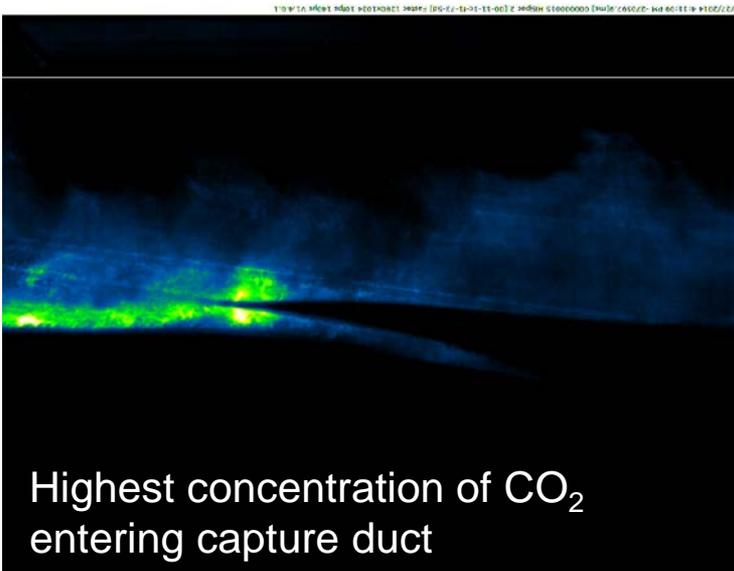
6 liquid throttle solid CO₂ injectors



Laser Images – Flow Before Turn/Migration

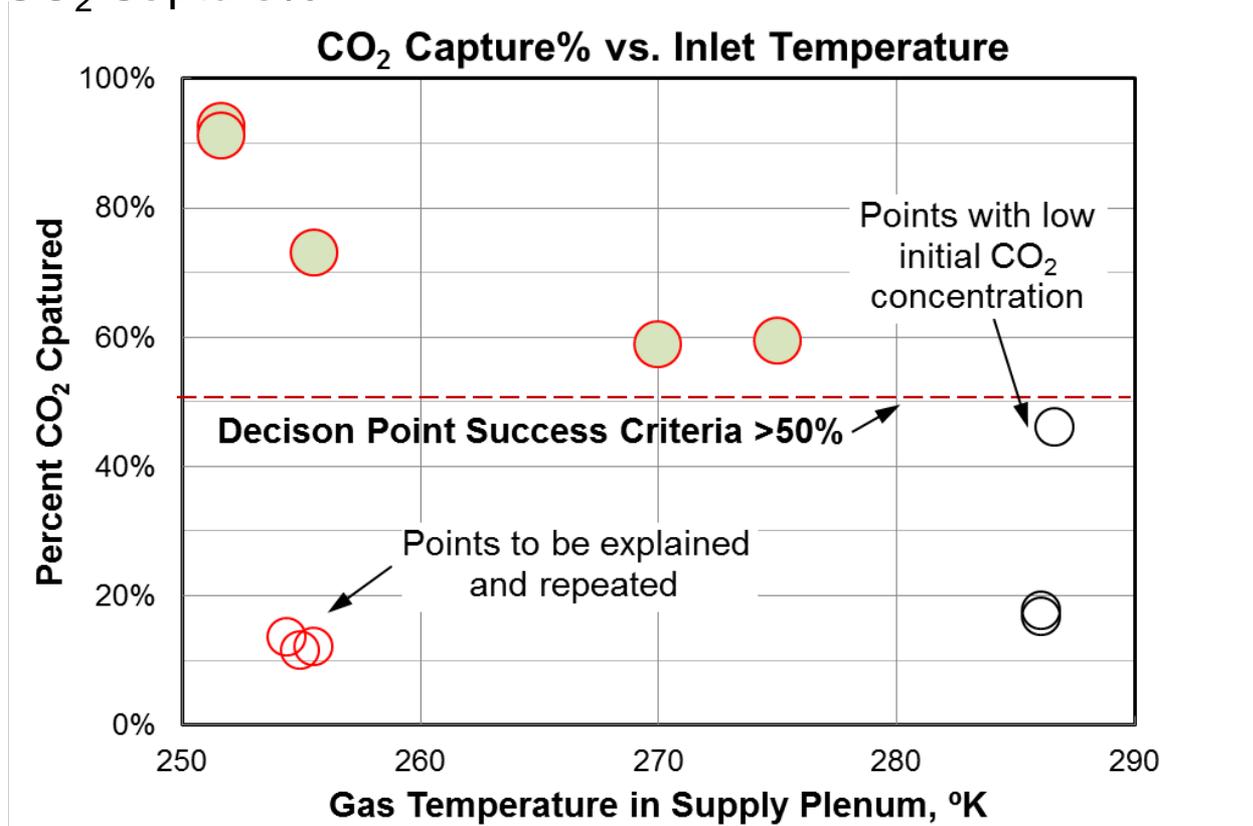


Laser Images from Capture Region



CO₂ Capture Results (Preliminary)

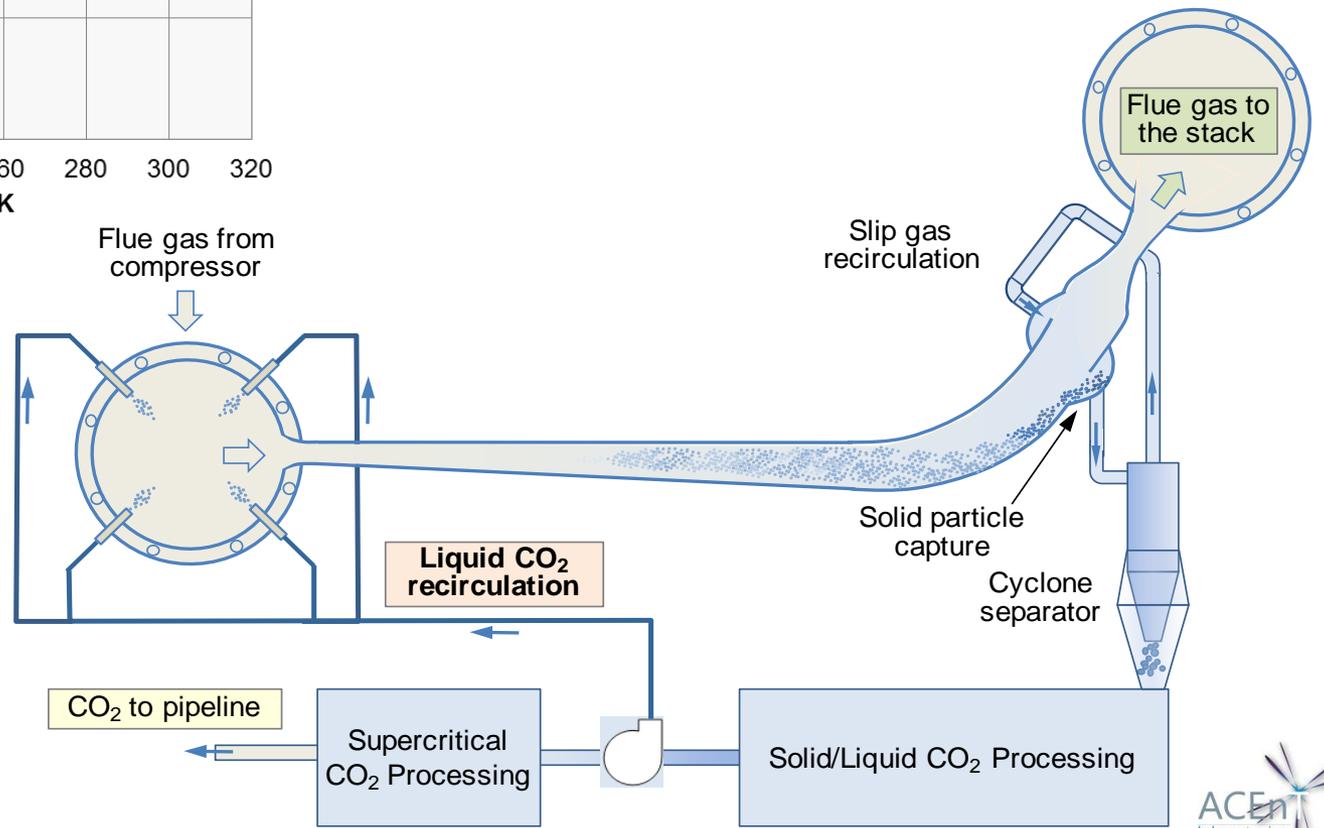
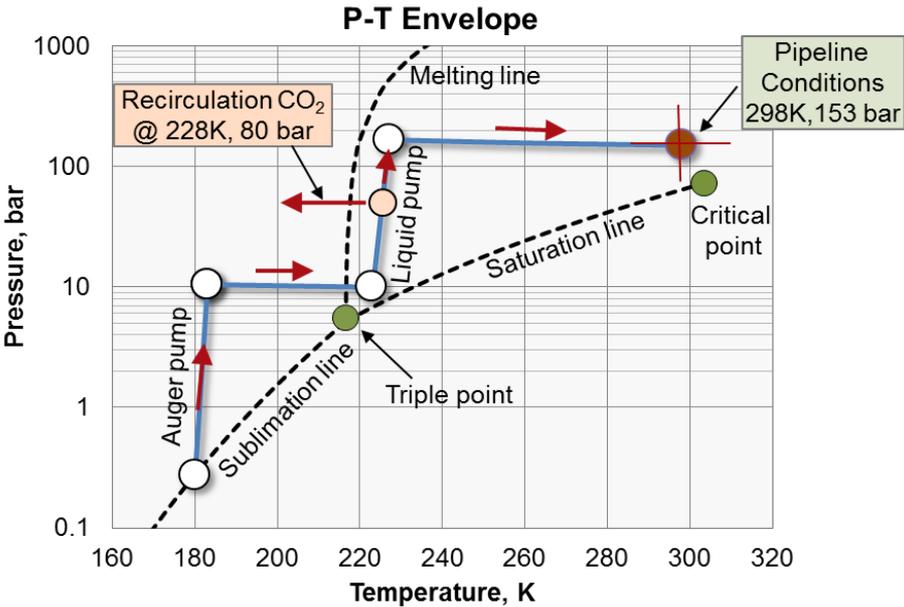
GC analysis of gas sample from primary (CO₂-depleted) flow stream used to calculate CO₂ Capture%



Most data consistent with good-to-excellent performance when incoming temperatures are somewhat colder. Thought to promote earlier heterogeneous nucleation onto existing CO₂ particles.

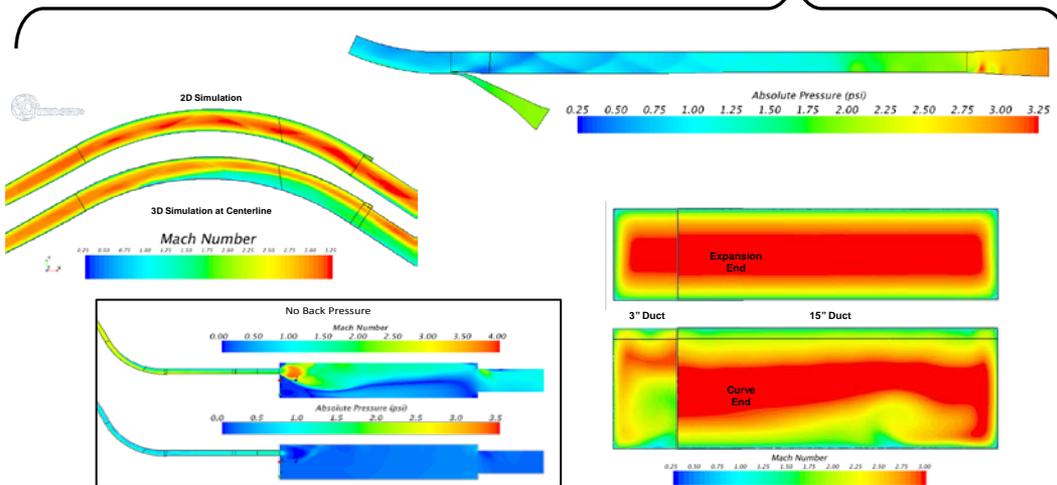
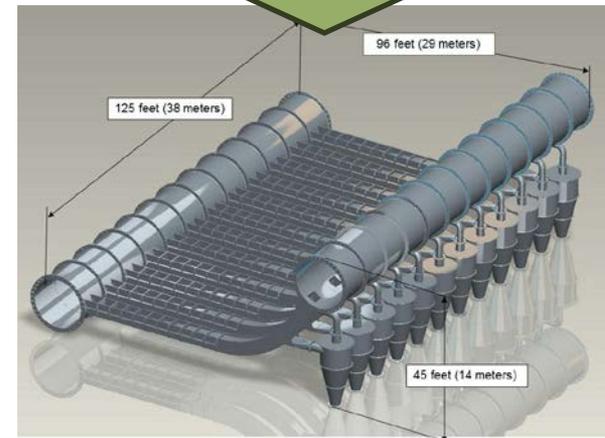
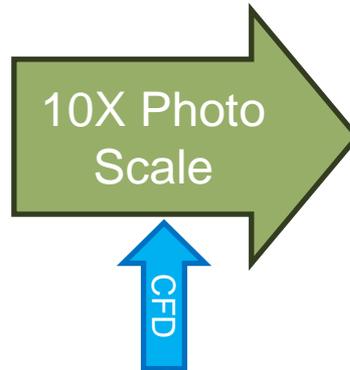
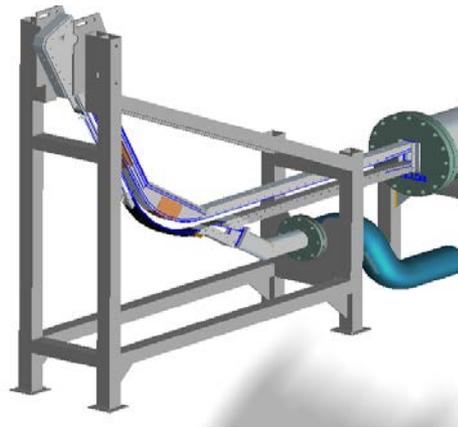
CO₂ Recirculation Approach

Recirculation of liquid CO₂ can achieve the desired results of additional cooling + creation of large particles to promote heterogeneous nucleation capable of migration.



CFD Tool Benchmarking for Full Scale Pressure Recovery Predictions

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Current scale limits pressure recovery performance due to thick boundary layer relative to duct size. We are on track to show traceability and path towards target pressure recovery of 40% through

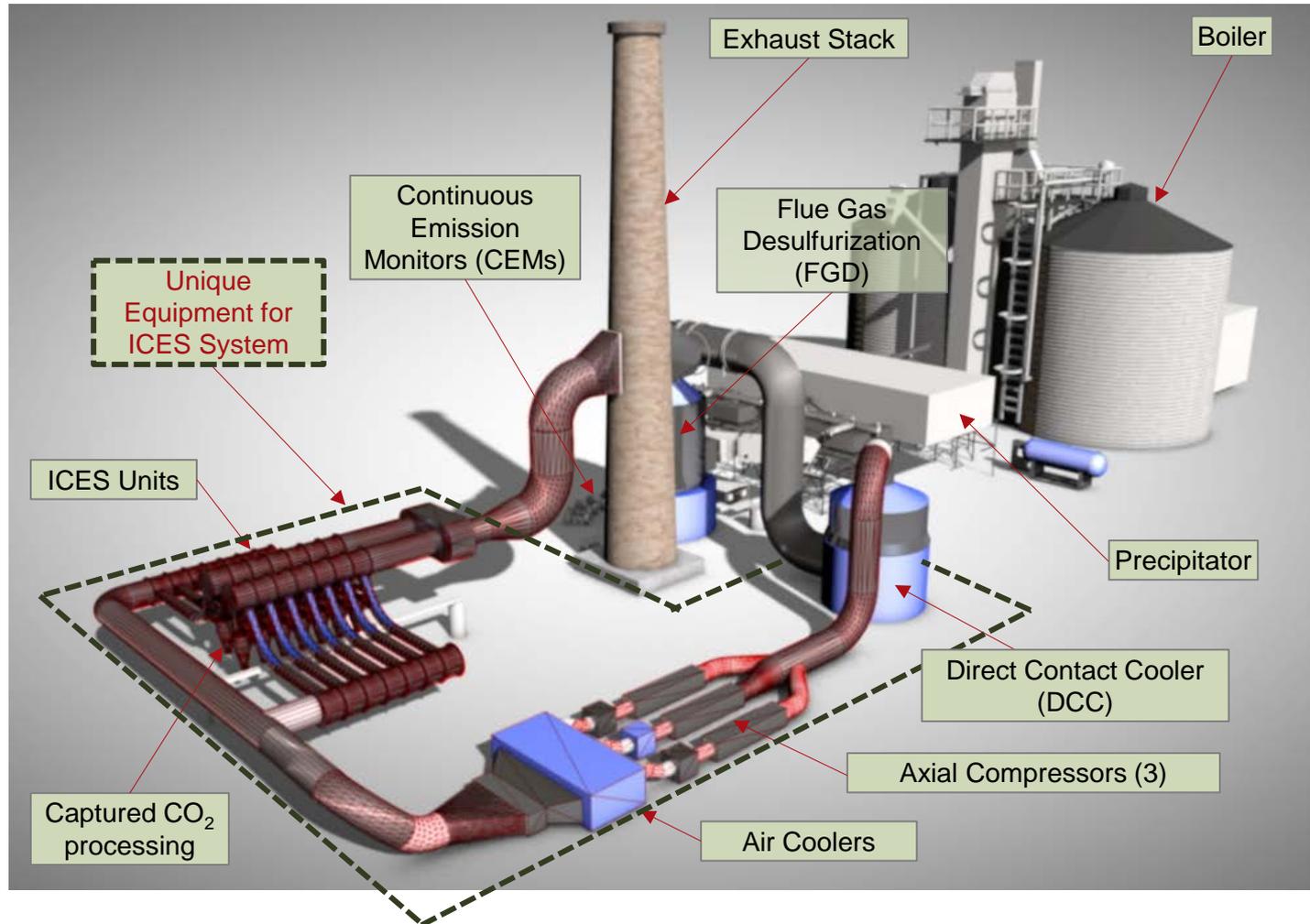
- CFD tool benchmarking using subscale test results (complete)
- CFD predictions of full scale performance

- A preliminary Techno-economic assessment by WorleyParsons (WP) was carried out in 2013
- Key efficiency/economic numbers are provided in the table below:

Metric	Case 11	Case 12, Amine Plant	ICES Plant
CO ₂ capture	no	yes	yes
Net plant efficiency (HHV basis)	39.3%	28.4%	34.5%
COE % increase	base	77%	42%
Parasitic Load	5.5%	20.5%	7.3%
Cost per tonne of CO ₂ captured	NA	US\$ 62.8	US\$ 41.8
Cost per tonne of CO ₂ avoided	NA	US\$ 90.7	US\$ 48.4

A path to the DOE research goal of 35% COE increase is being developed based on a more detailed capex/labor model and reduced flue gas compression (PR=2.0 vs 2.5 used in WP analysis)

ICES Plant Layout and Footprint



ICES footprint of ~8k m² compares to 20k to 30k m² for an amine plant of similar capacity. ICES nozzle and compressor stacking can further reduce footprint by 30-40%.

Project Schedule



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	Budget Period 1				Budget Period 2				Budget Period 3			
	Quarters											
Tasks	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1. Program Management												
Task 2. Lab-scale Condensation/Growth Investigation												
Task 3. Analytical and Computational Investigation												
Task 4. Bench-scale Capture and Diffuser Testing												
Task 5. Bench-scale Condensation/Growth Testing												
Task 6. Integrated System												
Task 7. Plant Integration and Techno-economic Analysis												



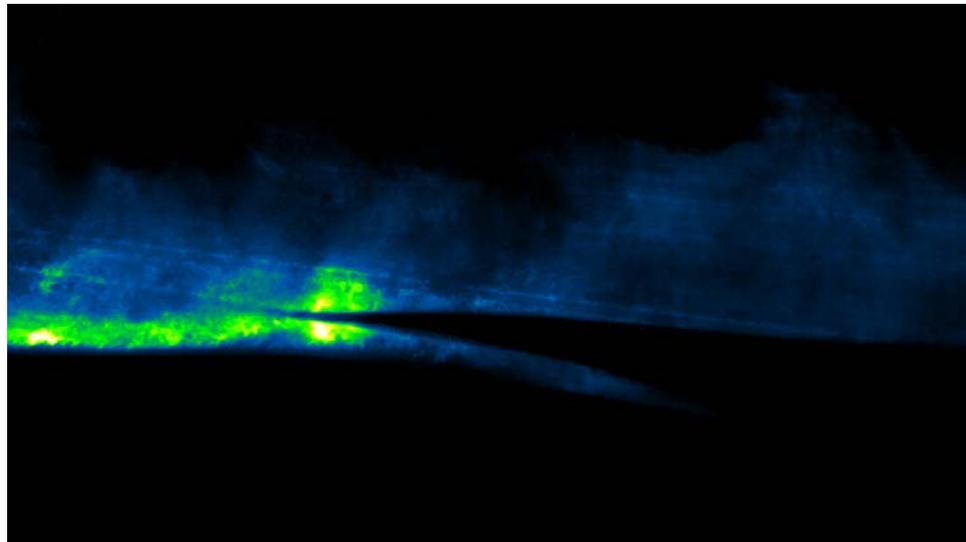

MS1 MS2 MS3

MS 1. Updated project management plan – **complete**

MS 2. Kickoff meeting - **complete**

MS 3. Capture duct/diffuser demonstration – **on track**

- ICES Technology holds considerable promise as an alternative to adsorbents and membranes
- Current NETL effort focused on solving key technical challenge of particle size
- Testing and analysis results to-date support project goals for capture efficiency and economics
- Program is on track to meet Budget Period 1 decision point success criteria
- We're moving fast (about Mach 3) and have promising results so far !



- **NETL**
 - Andy O’Palko
 - Lynn Brickett
 - Michael Matuszewski
- **ATK**
 - Florin Girlea
 - Michele Rosado
 - Dr. Daniel Bivolaru
 - Kirk Featherstone
- **ACENT Labs**
 - Dr. Pat Sforza
 - Randy Voland
 - Robert Kielb
- **Ohio State University**
 - Professor Barbara Wyslouzil
 - Dr. Shinobu Tanimura
- **WorleyParsons**
 - Dr. Jim Simpson
 - Dr. Vladimir Vaysman
- **EPRI**
 - Dr. Abhoyjit Bhowan
- **NYSERDA**
- **NYS-DED**