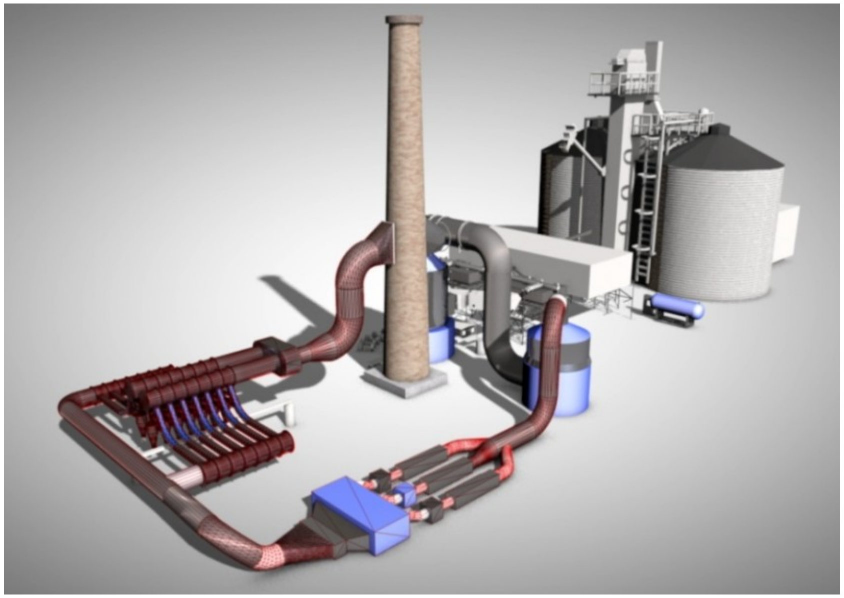
# Supersonic Post-Combustion Inertial $CO_2$ Extraction System

## Bench Scale Project Status Update

**2014 NETL $CO_2$ Capture Technology Meeting**

**Pittsburgh, PA**

**24 June 2015**



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**Andrew Robertson**

**Jason Tyll, Ph.D.**

# Project Overview

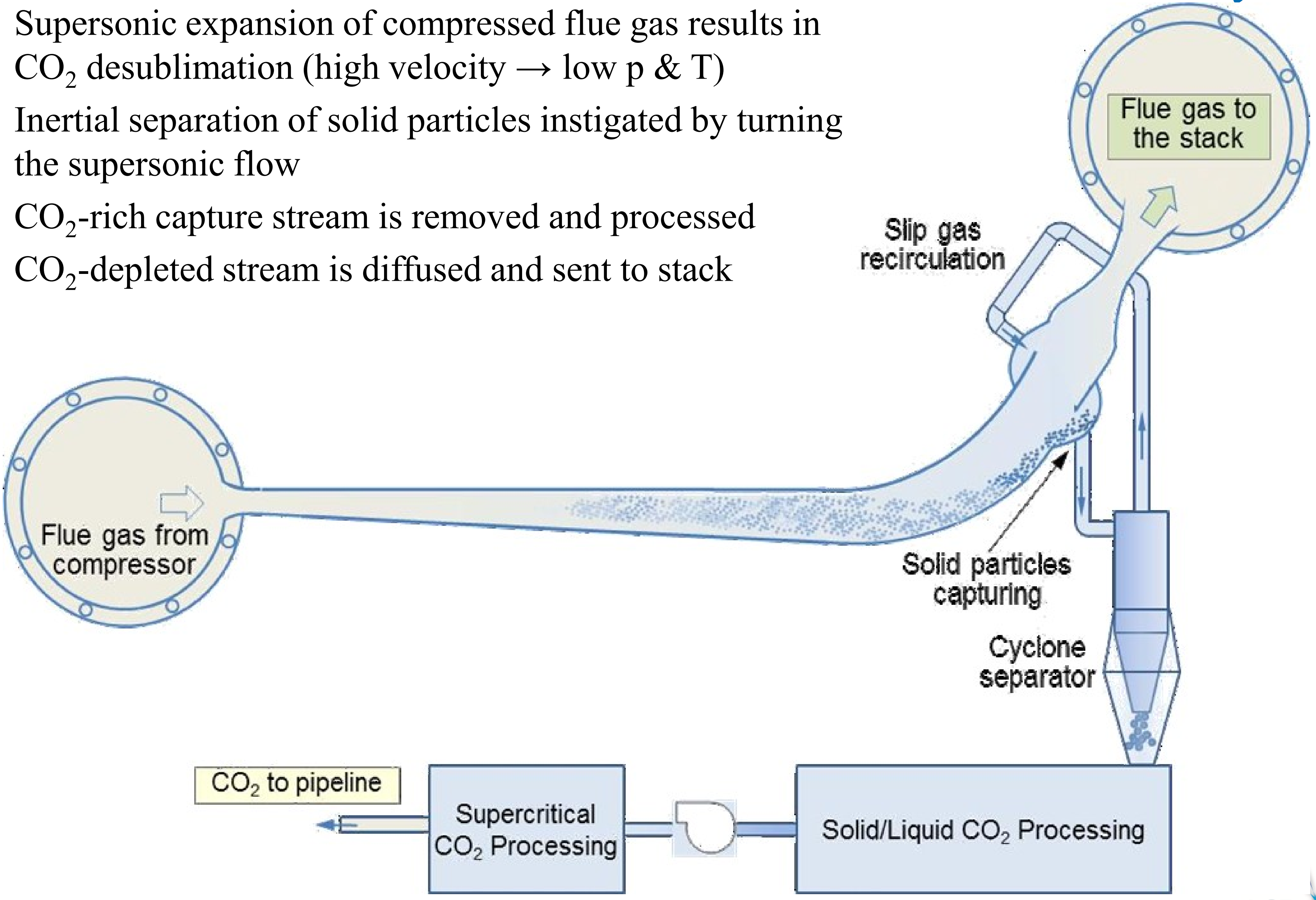
- **Funding**

| | |
|---|---|
| NETL: | $ 2,999,673 |
| Cost Share: | $ 749,918 |
| Total: | $ 3,749,591 |

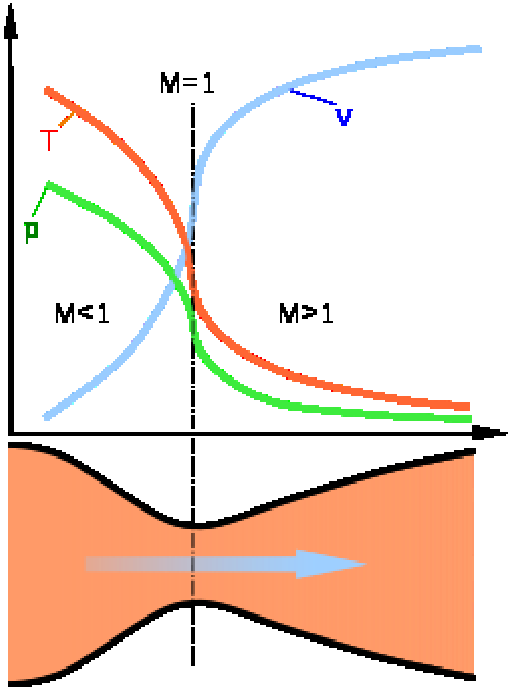
- **Project Performance Dates**
  - 1 Oct 2014 - 30 Sep 2017
- **Project Participants**
  - ATK & ACENT Laboratories
  - Ohio State University
  - EPRI
  - NYSERDA and NYS-DED
- **Project Objectives**
  - Demonstrate inertial $CO_2$ extraction system at bench scale
  - Develop approaches to obtain condensed $CO_2$ particle size required for migration
  - Demonstrate pressure recovery efficiency of system consistent with economic goals
  - Demonstrate $CO_2$ capture efficiency

# ICES Technology Background

- Supersonic expansion of compressed flue gas results in $CO_2$ desublimation (high velocity → low p & T)
- Inertial separation of solid particles instigated by turning the supersonic flow
- $CO_2$-rich capture stream is removed and processed
- $CO_2$-depleted stream is diffused and sent to stack

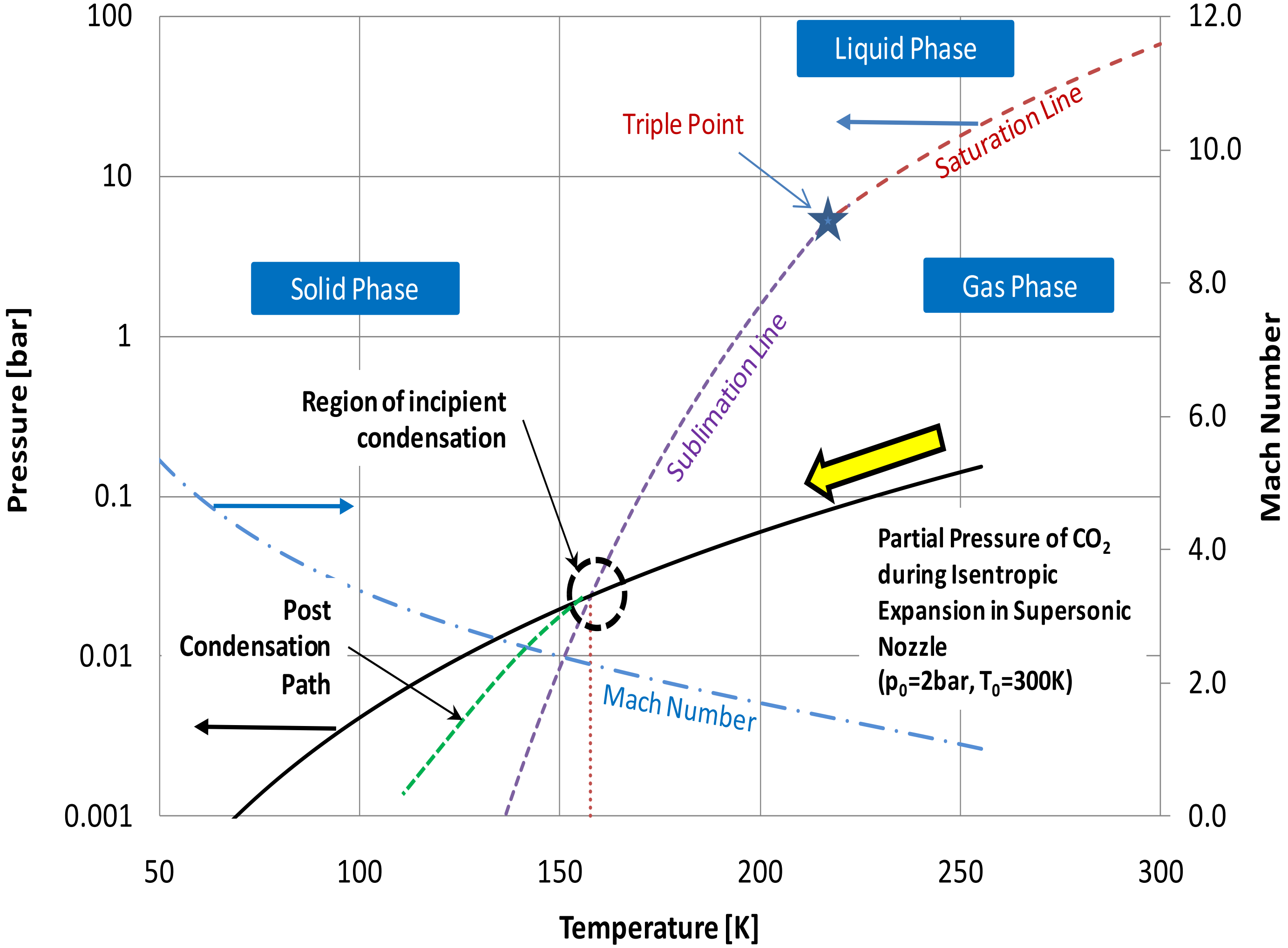


# Thermodynamics of ICES



Static pressure (p), static temperature (T) and velocity (v) in a converging-diverging nozzle

**Isentropic Expansion of 14mol% $CO_2$ in $N_2$ Relative to Phase Diagram of $CO_2$**



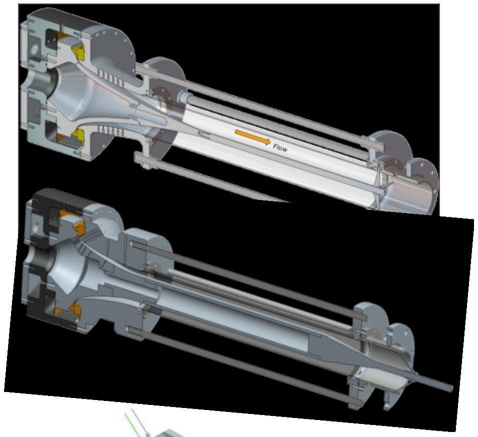
Low static pressure and temperature in supersonic nozzle causes $CO_2$ to precipitate as a solid – need to remove before diffusing back to low speed

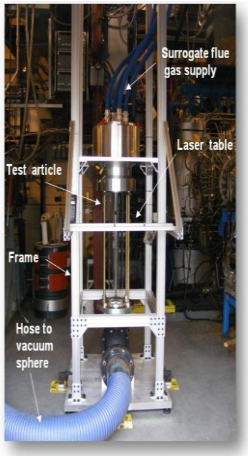
# Key Advantages and Challenges

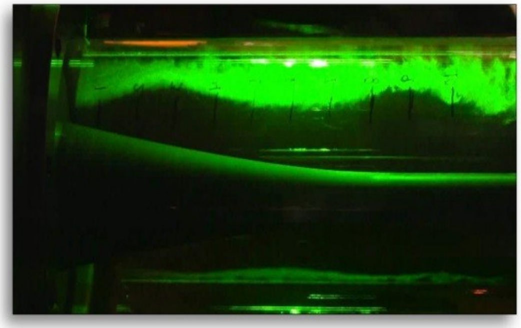
| Advantages | Challenges |
|---|---|
| No moving parts, chemicals/additives or consumable media | Maximization of $CO_2$ particle size with limited residence time |
| Inexpensive construction (sheet metal, concrete) | Minimization of "slip gas" removed with solid $CO_2$ |
| Small footprint (current 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 ARPA-e IMPACCT Activity

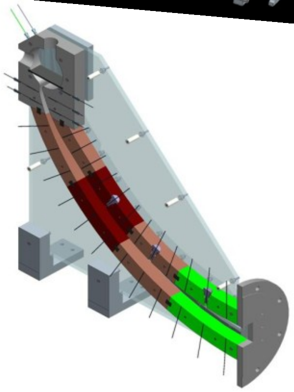
**Gen1a and 1b (swirl)**

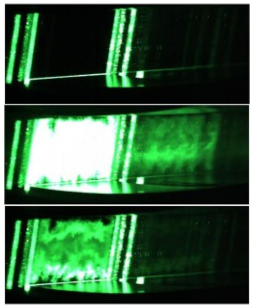




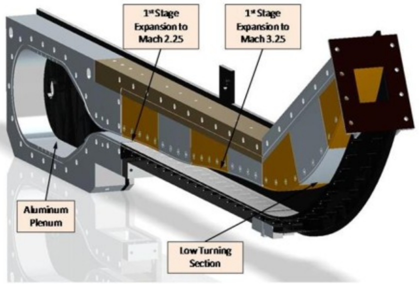


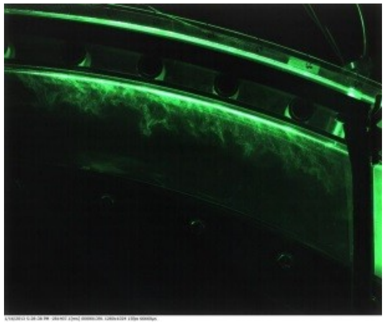
**Gen2 (2D)**





**Gen3 (2D - long)**





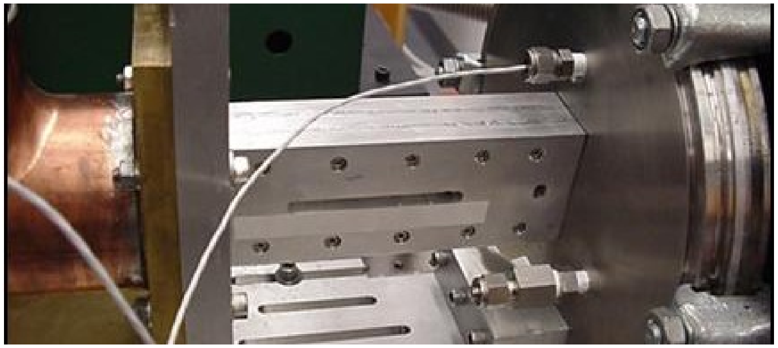
Principal conclusion of this effort was that $CO_2$ particles >2.5µm are required for efficient operation - need to control particle size generated

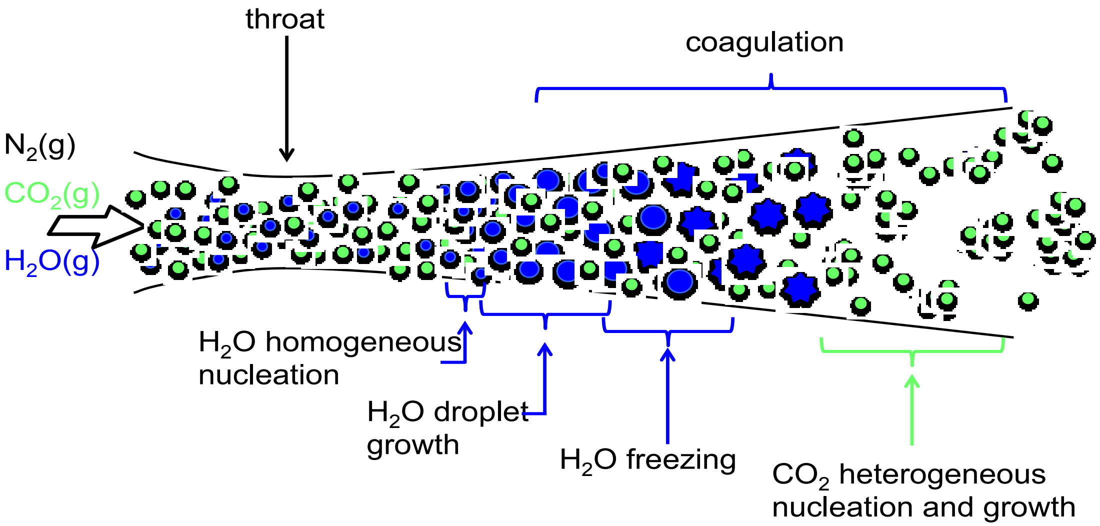
# Program Plan for Current Effort

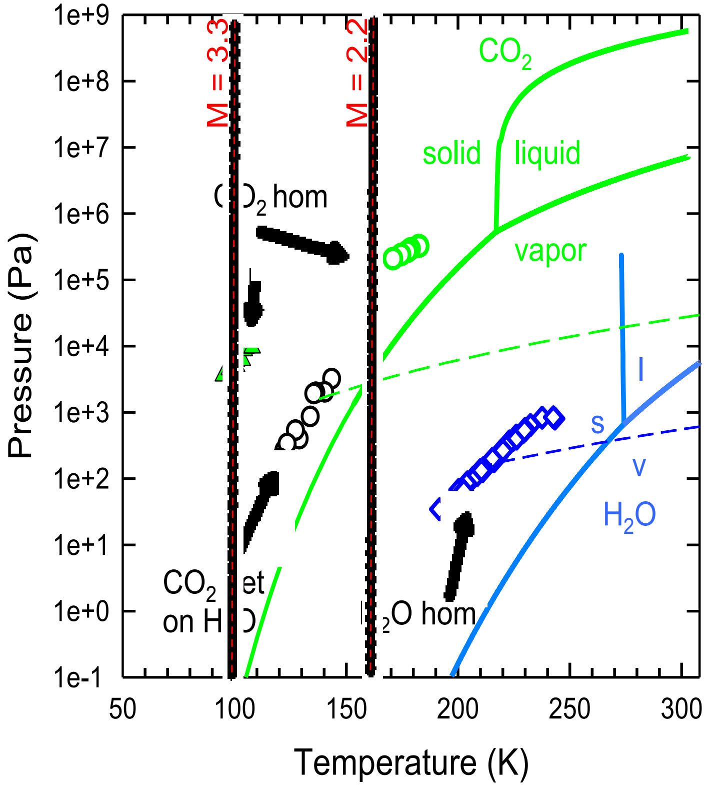
- **Year 1**
  - Lab-scale tests (OSU) to develop understanding of factors controlling particle size and methods to increase
  - Bench scale tests at ATK to demonstrate capture efficiency and diffusion with surrogate $CO_2$ injection (liquid throttle of $CO_2$ to produce controlled particle size)
  - 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 + $CO_2$ + $H_2O$)
  - Success criteria: Demonstrate migration of 80% of $CO_2$ to 20% of duct height and path to full scale 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

# Lab-scale Testing at Ohio State University

- Test program completed at OSU supersonic aerosol facility to gain better understanding of nucleation process, condensation rates, and particle size behavior



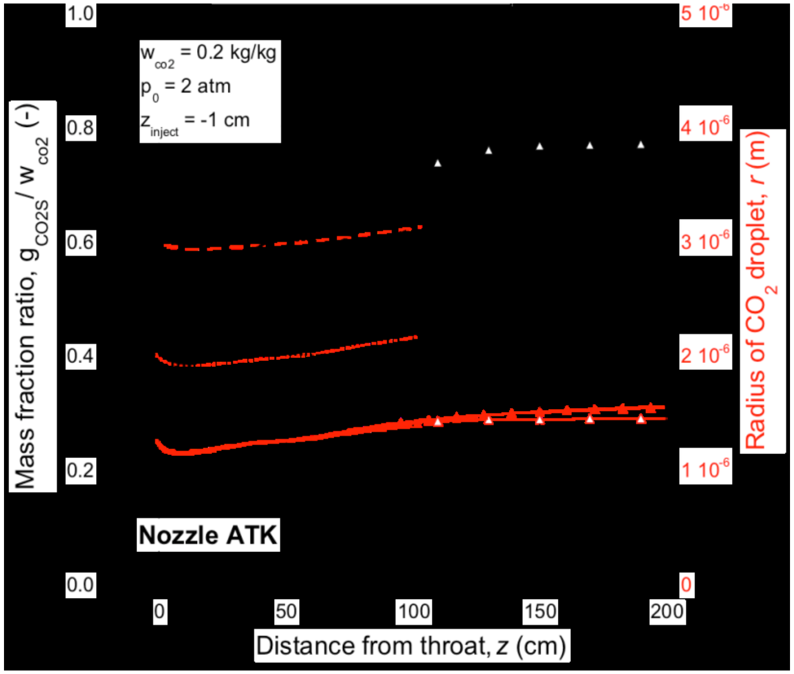


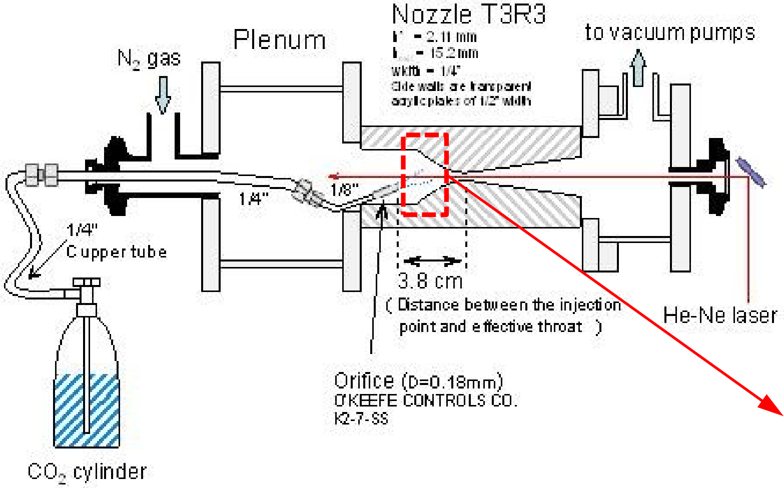


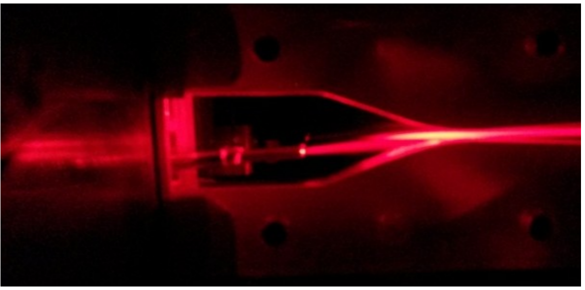
Initial test results proved that under our conditions, CO$_2$ only condenses on solid or liquid media in the flow (i.e. heterogeneous condensation)

# Lab-scale Testing at Ohio State University (continued)

- Test and analysis matrix included methods of inducing turbulent particle collisions to promote agglomeration
- These approaches proved to be too intrusive and resulted in local temperature increase
- Attention focused on solid $CO_2$ injection/seeding

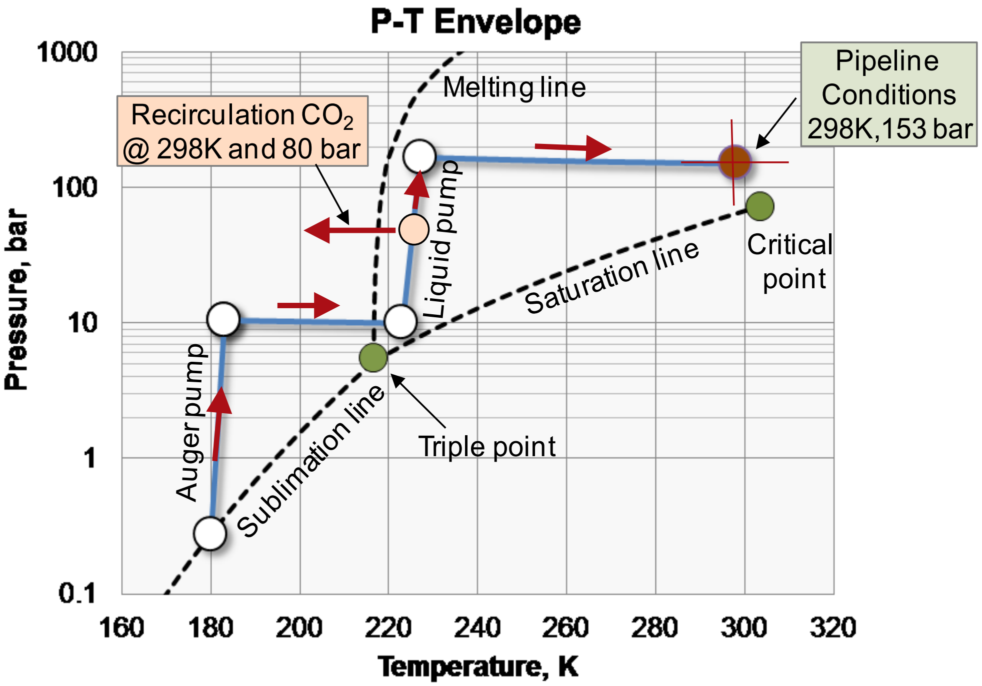




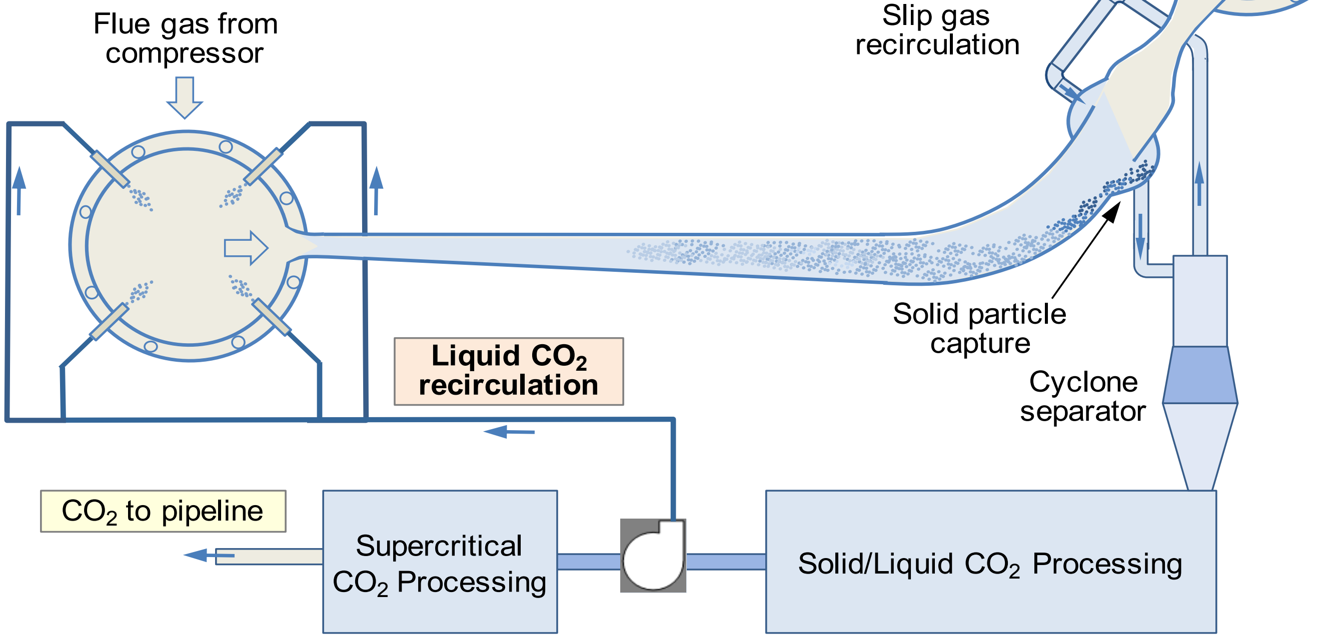


Combination of test data and detailed modeling led to conclusion that solid media (e.g. $CO_2$) seeding is most viable path to 90%+ capture by causing flue gas $CO_2$ to condense on particles already >2.5μm

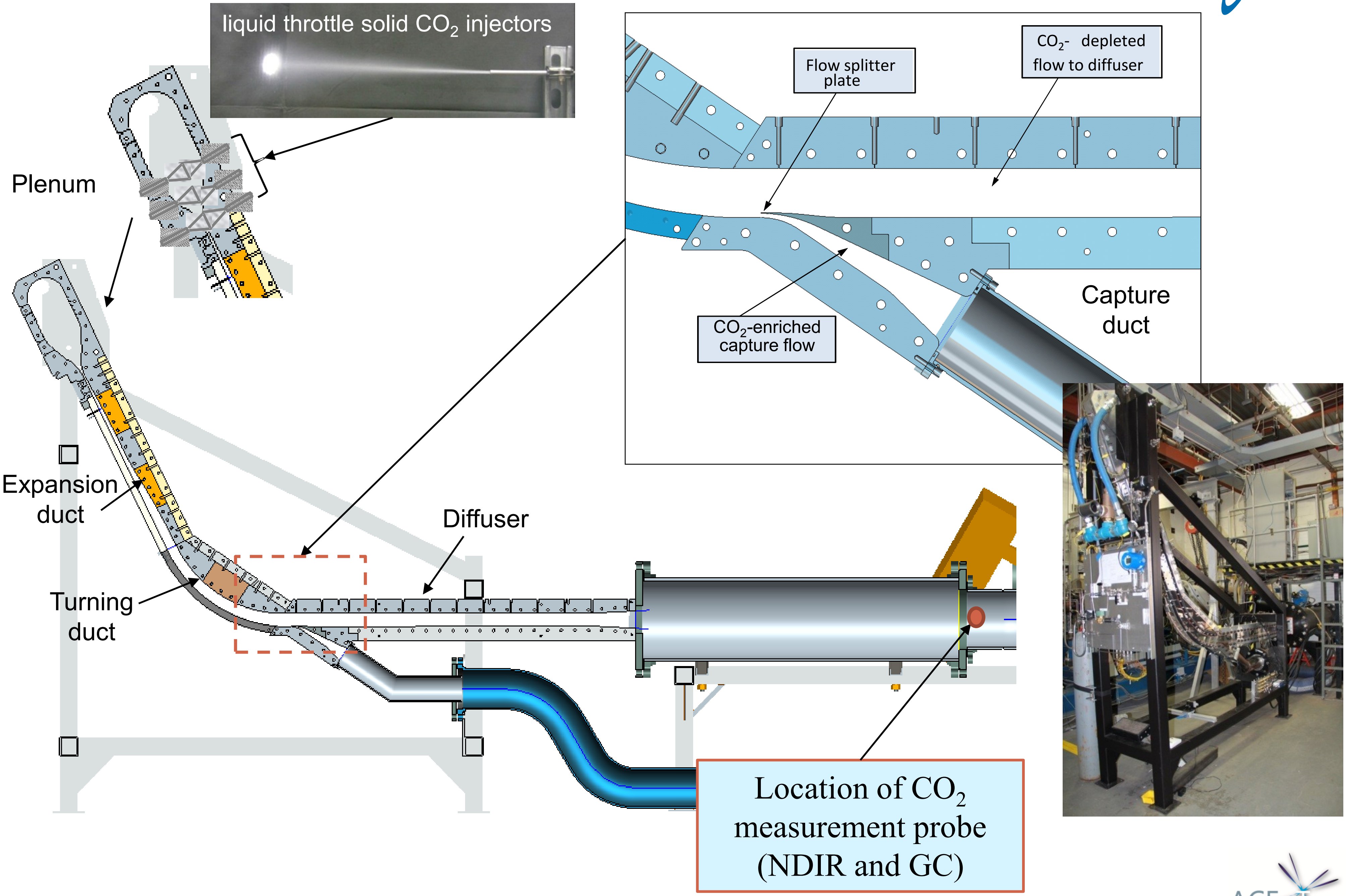
# One $CO_2$ Recirculation Approach



Recirculation of liquid $CO_2$ can achieve the desired results of additional cooling + creation of large particles to promote heterogeneous nucleation capable of migration. Requirement to inject very close to throat to mitigate evaporation.

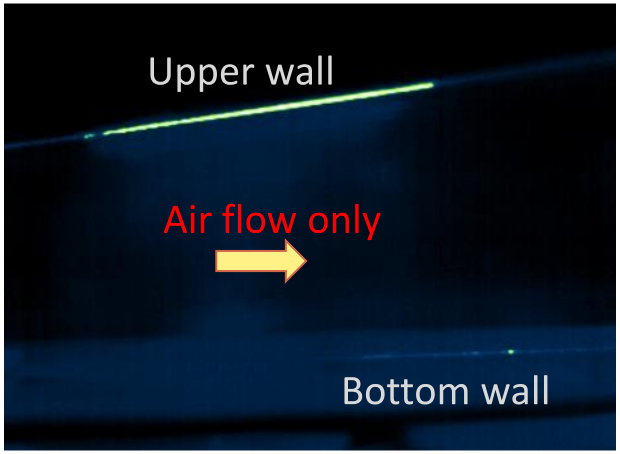


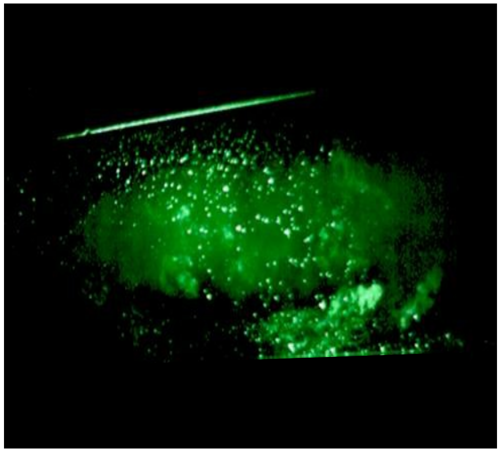
# Current Bench Scale Test Arrangement (250kW)

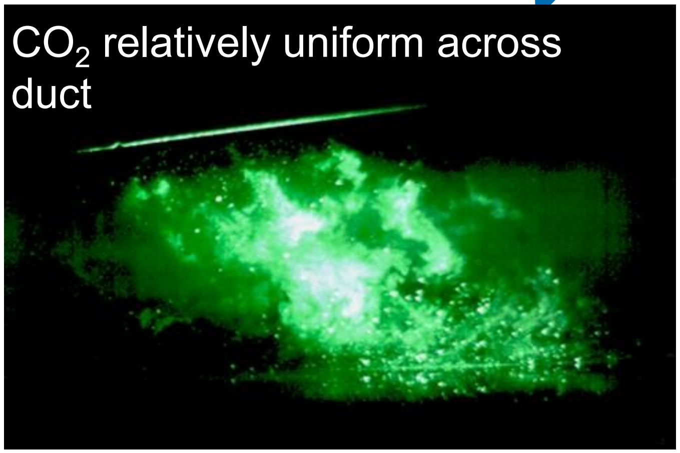


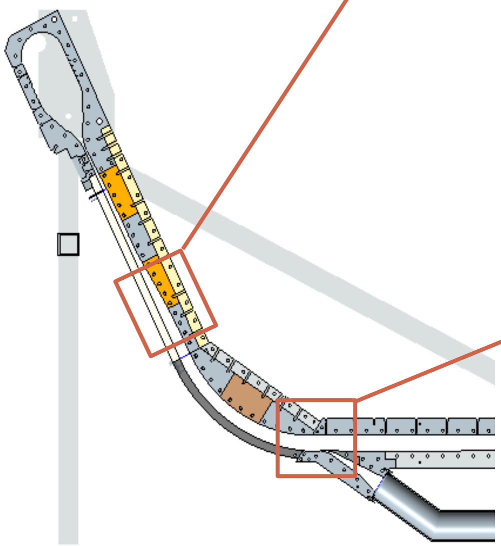
Location of $CO_2$ measurement probe (NDIR and GC)

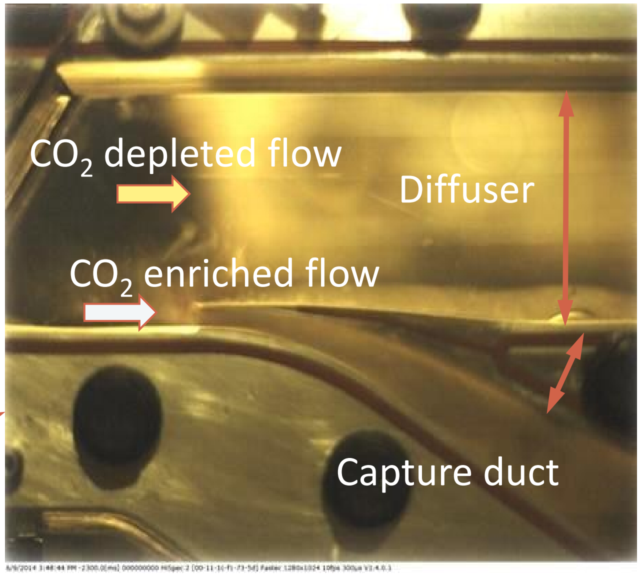
# Laser Images of $CO_2$ in Flow

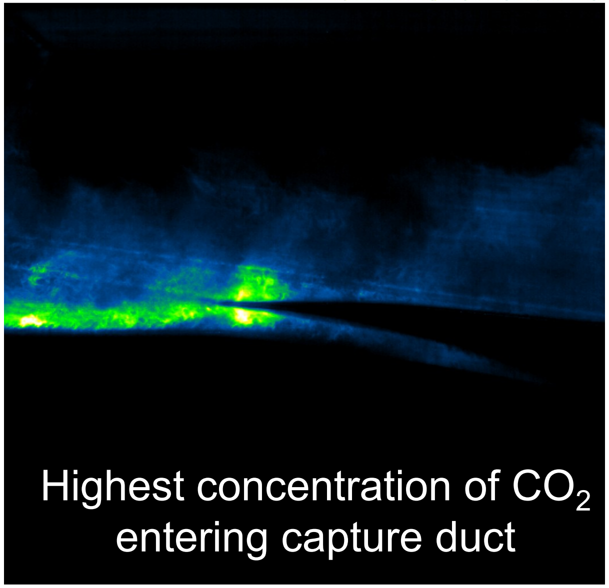





$CO_2$ relatively uniform across duct



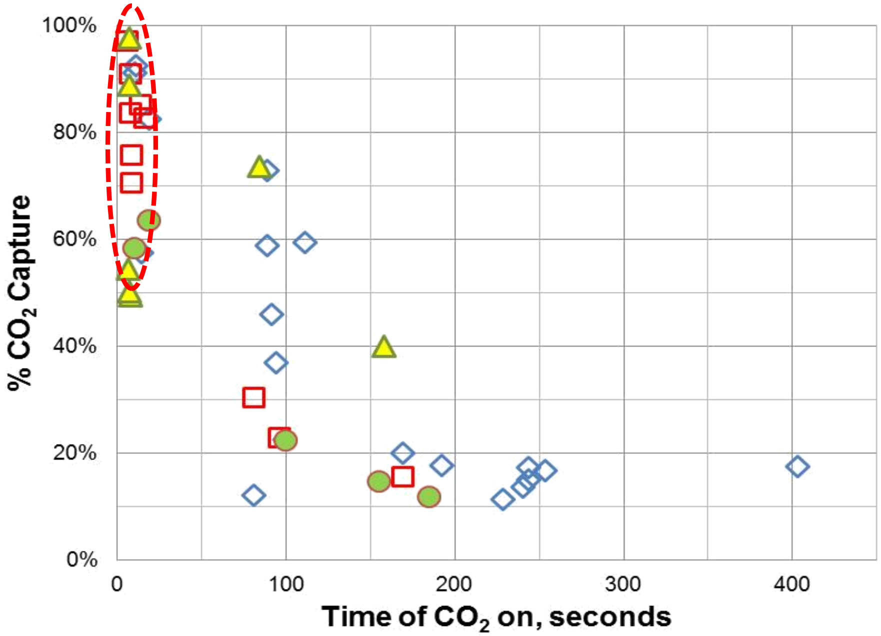



Highest concentration of $CO_2$ entering capture duct

# $CO_2$ Capture Data

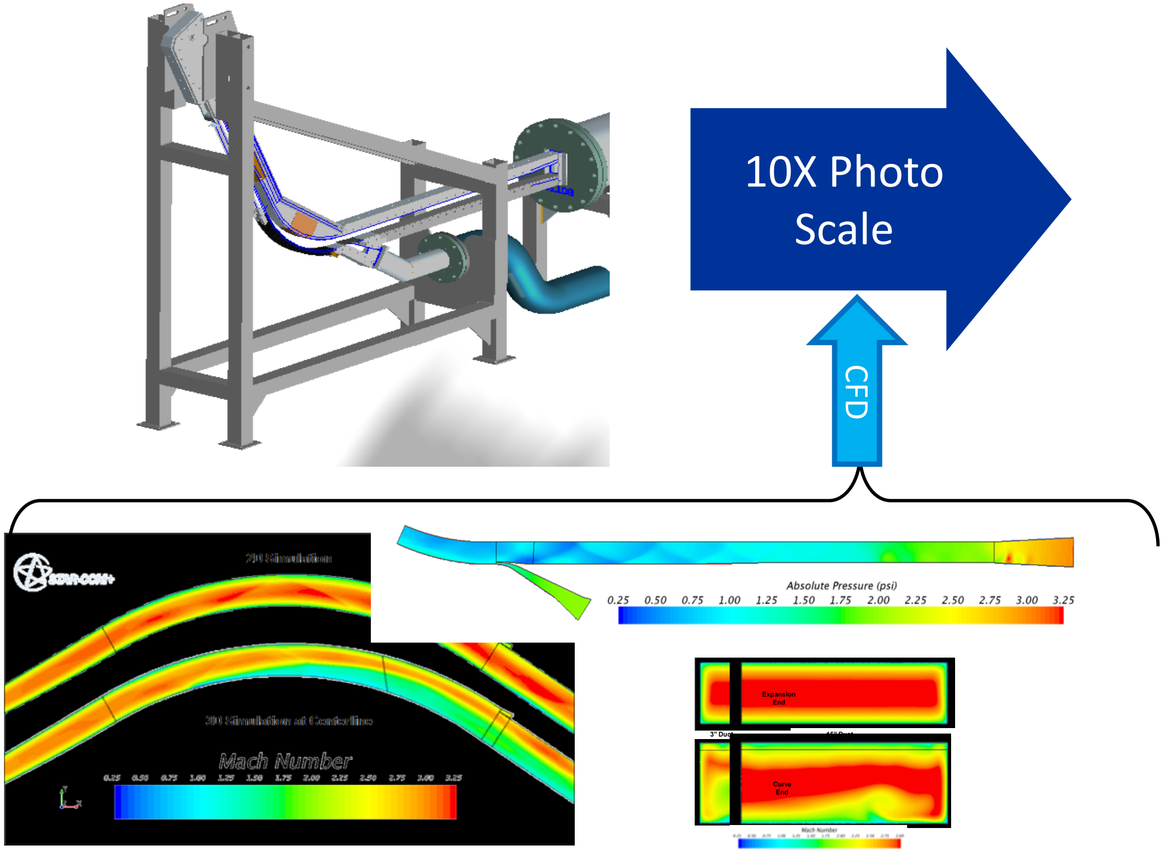
Gas samples taken from primary flow stream were processed with on-line gas chromatograph (GC) and NDIR sensors to access $CO_2$ mole fraction.

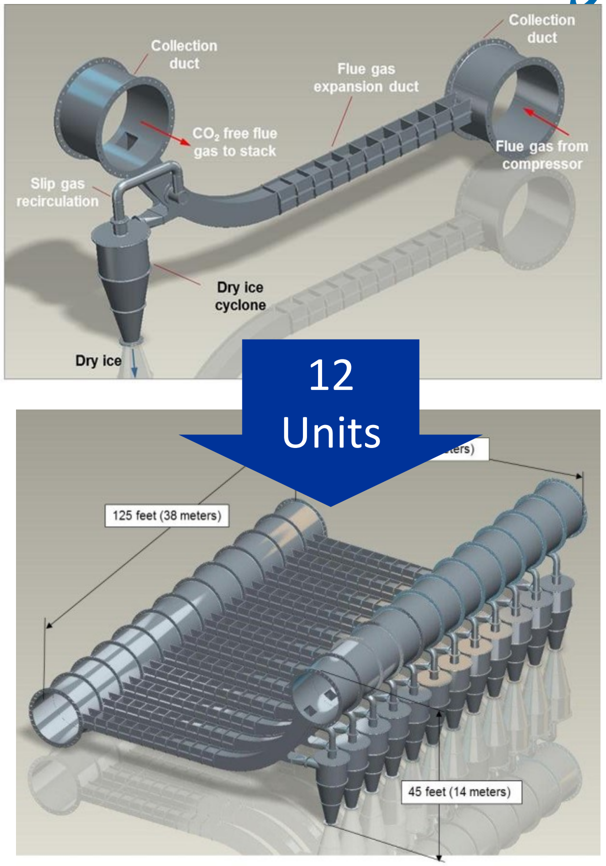
Last year - goal of capture >50% of $CO_2$ achieved for short duration tests. Cumulative measurement error due to GC and NDIR sensor contamination after first several seconds



This year – gas sample approach reworked to mitigate several sources of error including time lag, pump oil contamination + added in-situ calibration. Preliminary review of results indicate >50% capture of solid $CO_2$ in several recent tests – data still in detailed review

# Full Scale Pressure Recovery Predictions





Current scale limits pressure recovery performance due to thick boundary layer relative to duct size. We have shown path to target pressure recovery of 40% through:

- CFD benchmarking using subscale test results and predictions of full scale performance
- Definition of flowpath updates required to improve performance from 31% to 40% overall pressure recovery

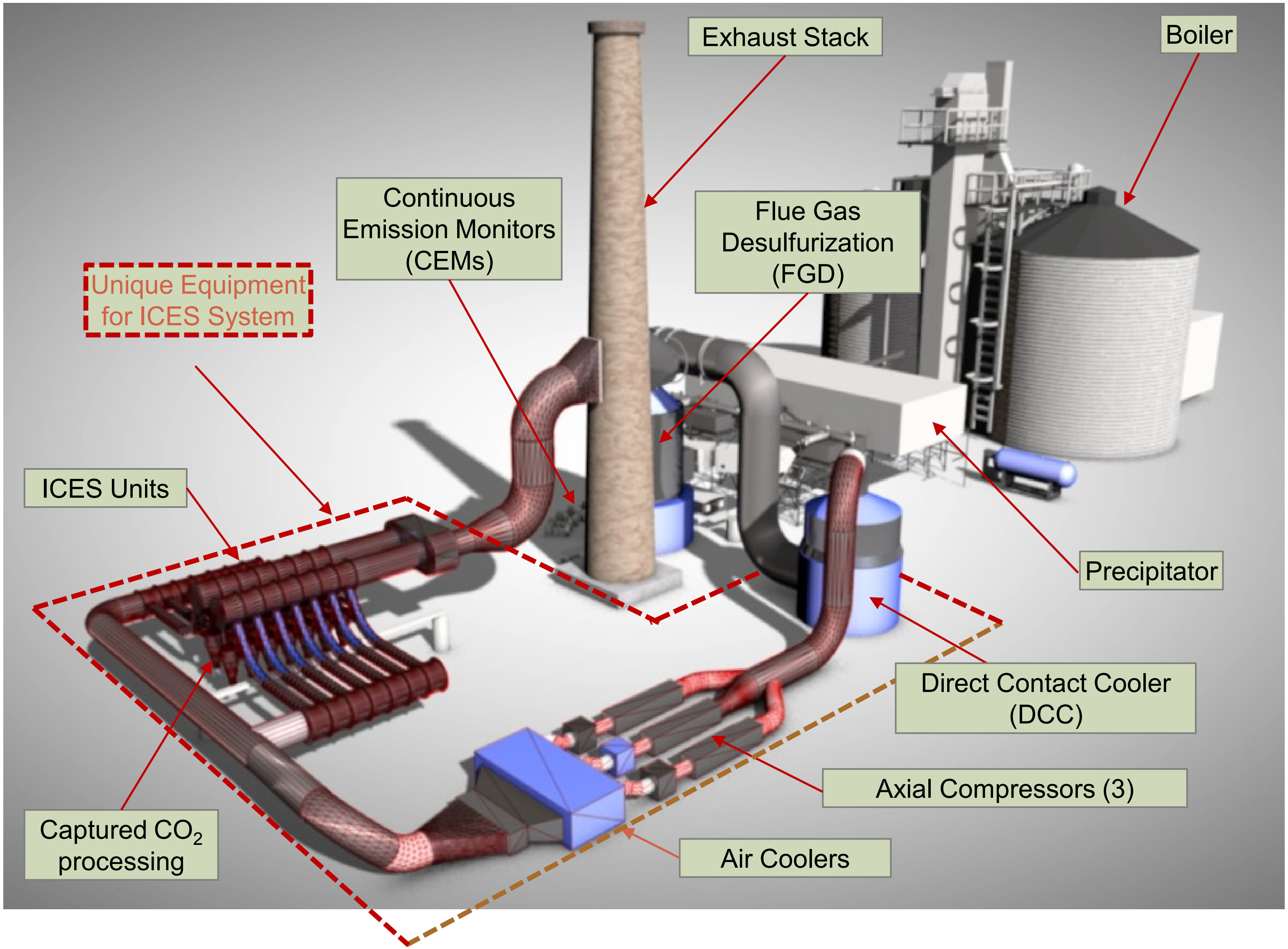
| Component | CFD Current Configuration | Desired Performance |
|---|---|---|
| Expansion Duct | 79 % | 85% |
| Turning Duct | 88% | 95% |
| Diffuser Duct | 45% | 50% |
| **Total** | **31%** | **40%** |

# ICES Economic Impact

- 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 |

# ICES Plant Layout and Footprint



Exhaust Stack

Boiler

Continuous Emission Monitors (CEMs)

Flue Gas Desulfurization (FGD)

Unique Equipment for ICES System

ICES Units

Precipitator

Direct Contact Cooler (DCC)

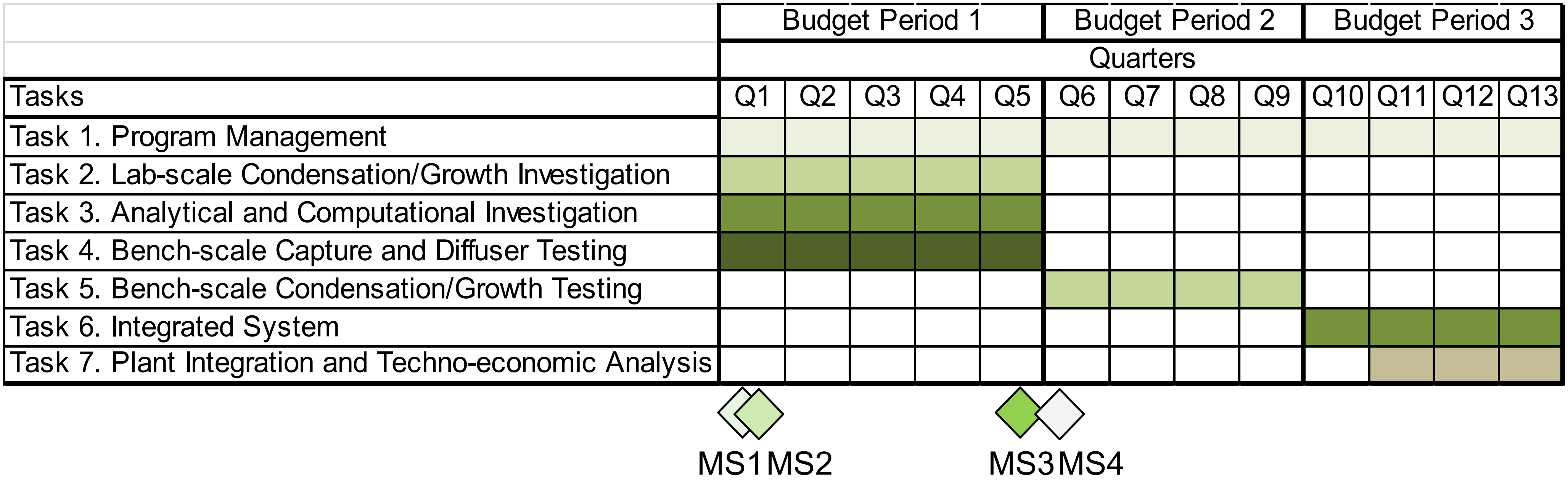
Axial Compressors (3)

Captured $CO_2$ processing

Air Coolers

ICES footprint of ~8k m$^2$ compares to 20k to 30k m$^2$ for an amine plant of similar capacity.
ICES nozzle and compressor stacking can further reduce footprint by 30-40%.

# Project Schedule

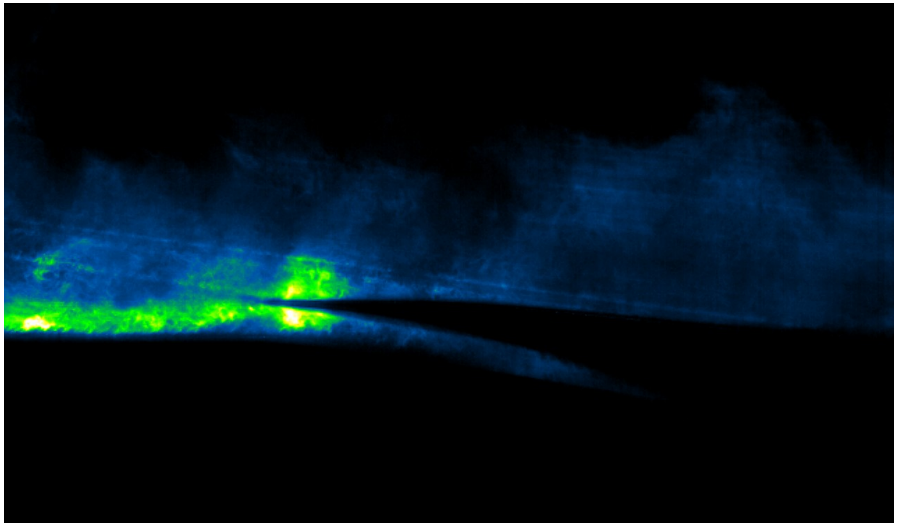


| | Budget Period 1 | | | | | Budget Period 2 | | | | Budget Period 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quarters | | | | | | | | | | | | |
| Tasks | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 |
| Task 1. Program Management | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 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 | | | | | | | | | | | 🟫 | 🟫 | 🟫 |

MS 1. Updated BP1 PMP – **complete**
MS 2. Kickoff meeting - **complete**
MS 3. Capture duct/diffuser demonstration – **complete**
MS 4. Updated BP2 PMP – **complete**

# Summary

- 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 strategy of solid $CO_2$ recirculation as most viable approach
  - Ongoing work to optimize $CO_2$ injection arrangement to minimize evaporation upstream of supersonic section and to redesign turning duct to increase pressure recovery performance



# Acknowledgements

- **NETL**
  - Andy O’Palko
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- **ATK**
  - Bon Calayag
  - Florin Girlea
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- **EPRI**
  - Dr. Abhoyjit Bhown
  - Adam Berger
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