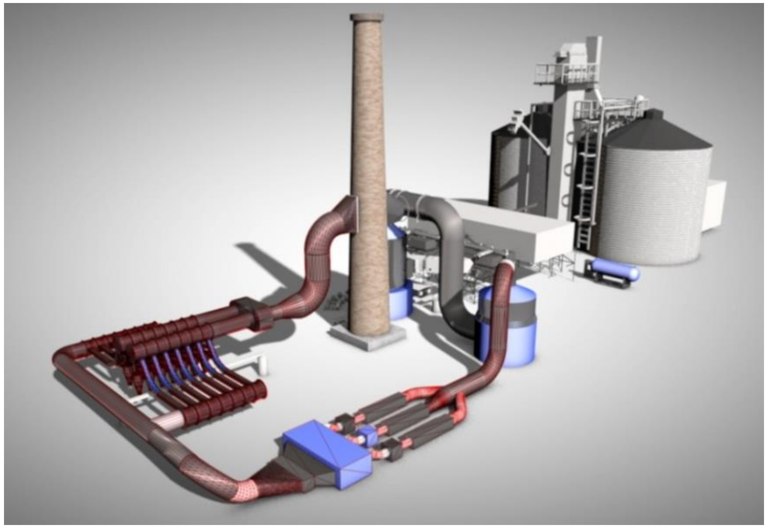
Supersonic Post-Combustion Inertial CO_2 Extraction System

Bench Scale Project Status Update

2016 NETL CO_2 Capture Technology Meeting

Pittsburgh, PA

10 August 2016



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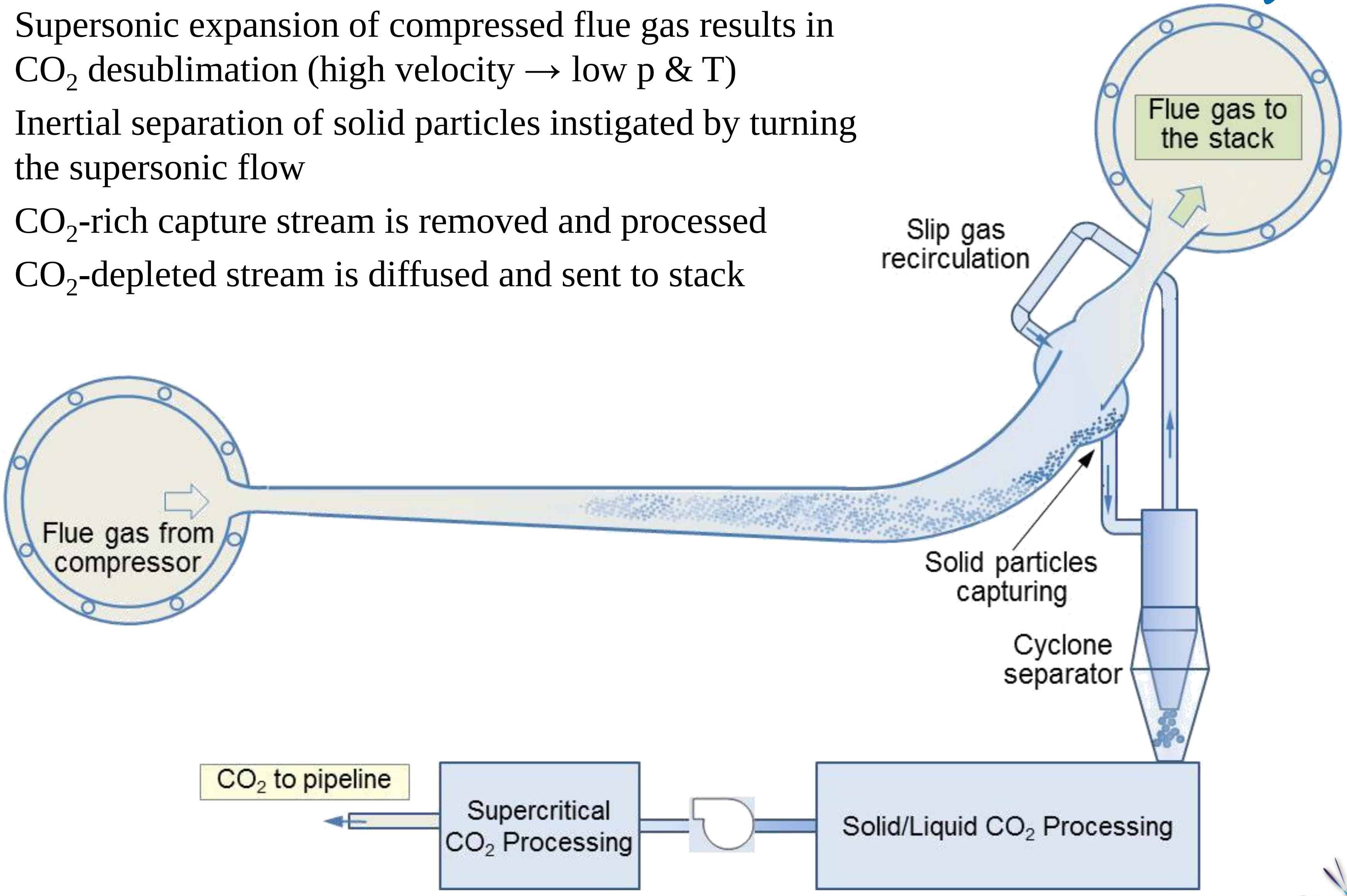
Project Overview

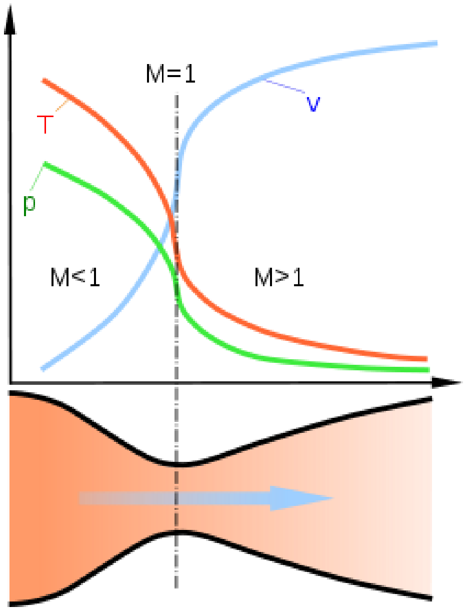
- **Funding**
  - NETL: $ 2,999,673
  - Cost Share: $ 749,918
  - Total: $ 3,749,591
- **Project Performance Dates**
  - 1 Oct 2014 - 30 Sep 2017
- **Project Participants**
  - ATK & ACENT Laboratories
  - Ohio State University
  - EPRI
  - NYSERDA and NYS-DED
- **Project Objectives**
  - Demonstrate 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

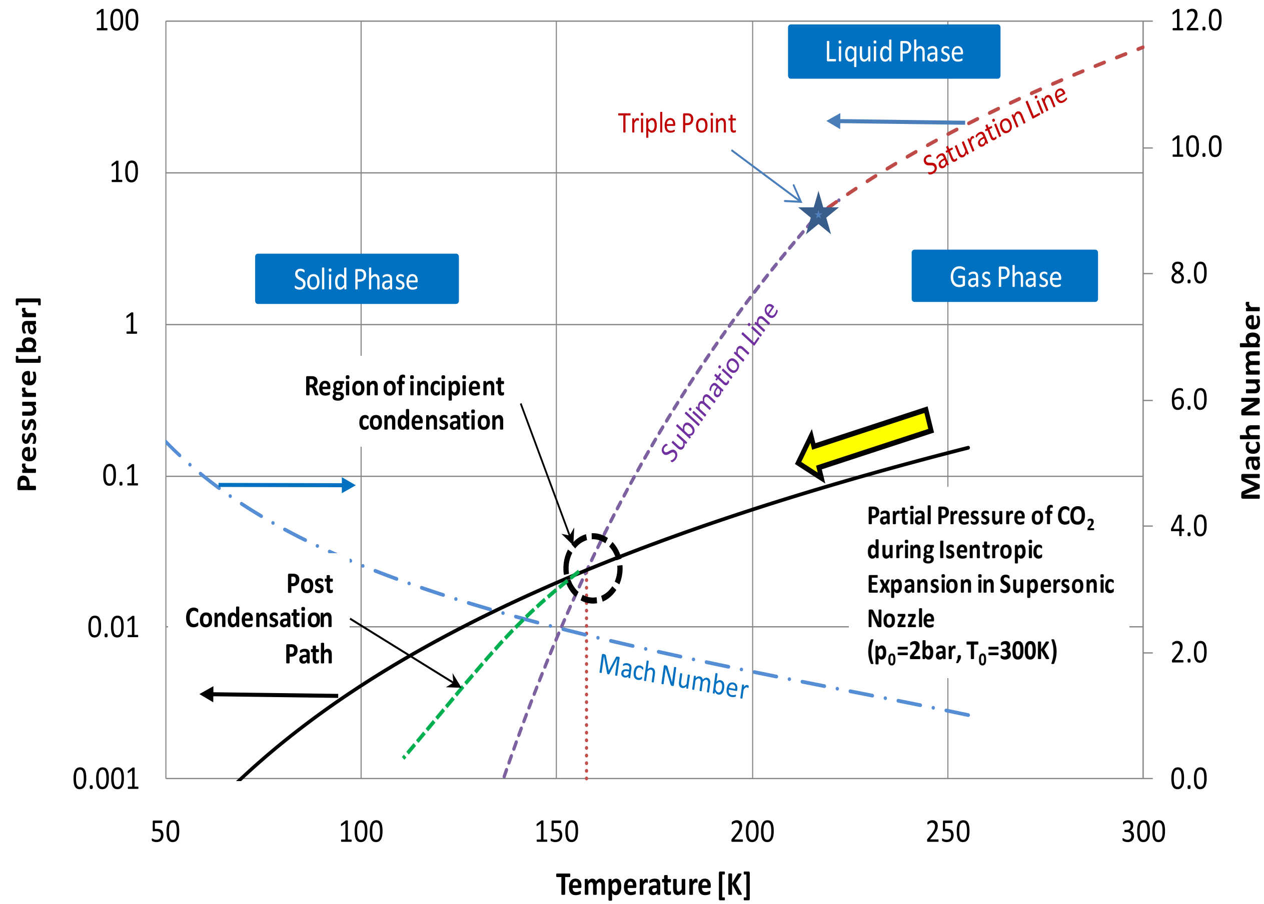
- Supersonic expansion of compressed flue gas results in CO_2 desublimation (high velocity → low p & T)
- Inertial separation of solid particles instigated by turning the supersonic flow
- CO_2-rich capture stream is removed and processed
- CO_2-depleted stream is diffused and sent to stack



Thermodynamics of ICES



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

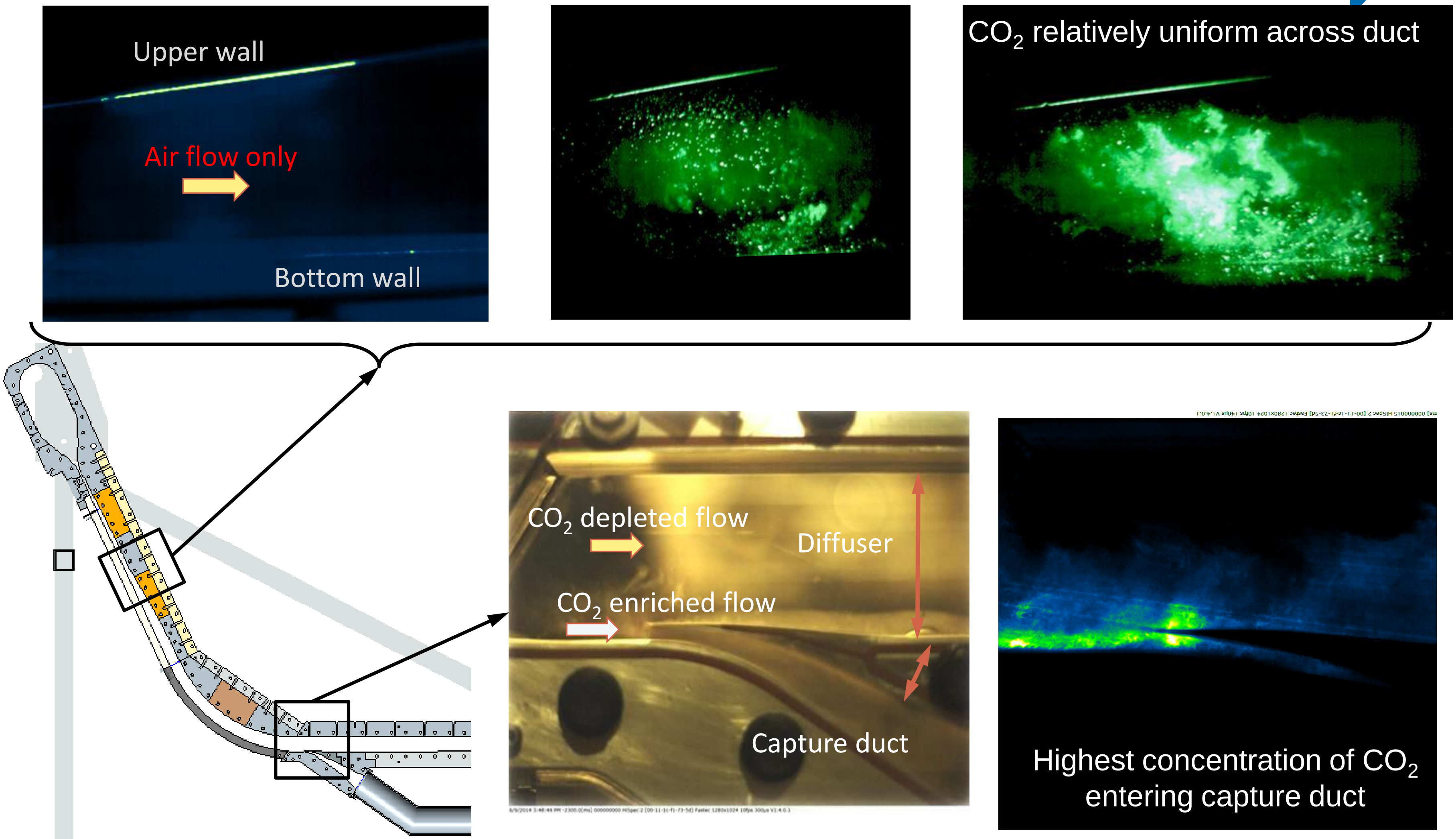


Low static pressure and temperature in supersonic nozzle causes CO_2 to precipitate as a solid – need to remove before diffusing back to low speed

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)	Optimization of flowpath pressure recovery
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	Minimization of “slip gas” removed with solid CO_2

Summary of Previous Results



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

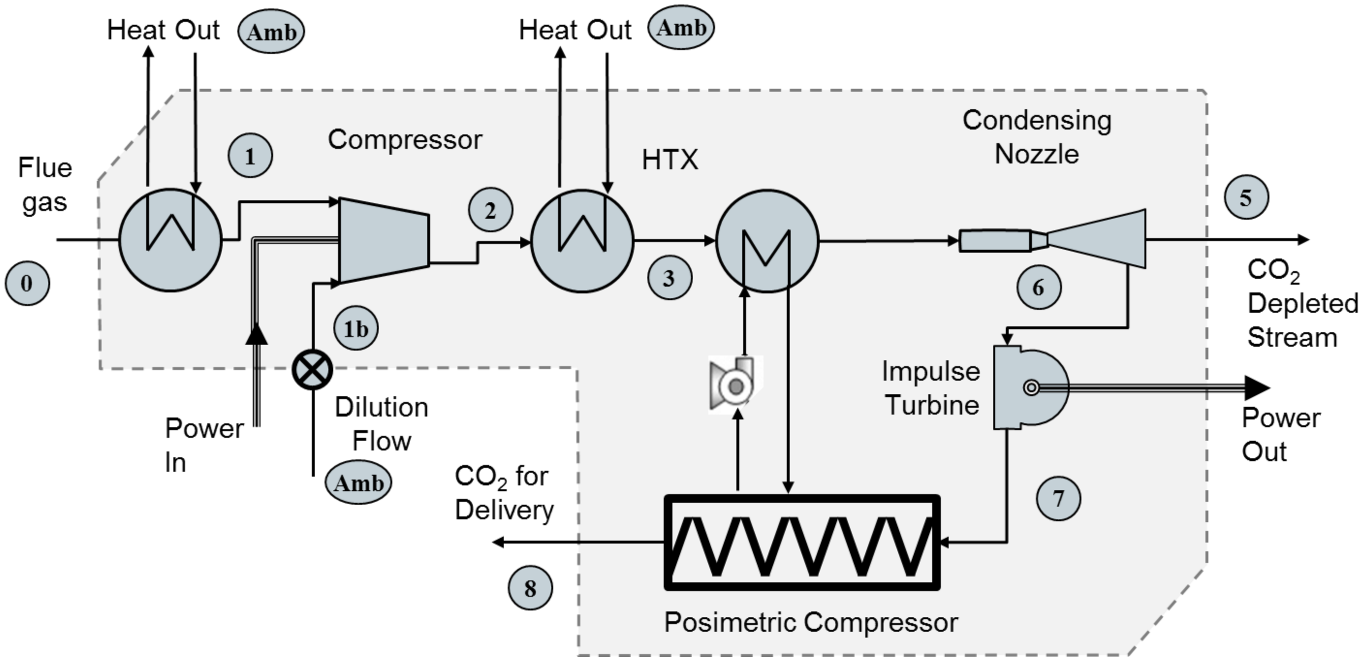
Program Plan for Current Effort

- **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 (as re-baselined)**
  - Demonstrate capability to create ~3µm+ CO_2 particles in subsonic region via precooling
  - Update previous techno-economic analysis to incorporate current flue gas compression and heat exchange requirements
  - Success criteria: CO_2 particles can be seen at the exit of the subsonic unit, visual observations and particle measurements confirm formation of particles of migrate-able size (e.g. > 3 microns), updated ICES configuration and heat & mass balance analysis shows path to viable system performance
- **Year 3** *(currently TBD pending Year 2 results)*
  - Integrated bench-scale testing with capture + diffuser
  - Success criteria: 75% capture with path to 90%, path to full scale pressure recovery

Program Update

- Thermodynamics of the ICES process has been modeled using higher-fidelity tools
  - Enabled by EPRI-developed extended Peng-Robinson model for state parameters including solid phase
- Results show lower pressure recovery than previously predicted (more compression required)
- Parametric study shows that flue gas compression ratios in the range of 5-8 are required if coupled with flue gas precooling, based on heat exchange with captured CO_2
  - Previous techno-economic analysis assumed a compression ratio of 2.5
  - Lower compression ratios possible with flue gas dilution with air – looking for optimum balance of overall energy input
- Requirement for large condensed particles (~3μm+) previously drove us to investigate seeding of flow with captured CO_2 or other particles to serve as nucleation media
  - Analysis shows that additional energy required to accelerate added mass to high speed is significant (assuming kinetic energy not recovered)
- **Pre-cooling using captured CO_2 as "cold sink" is new baseline** –subsonic condensation of trace water or small quantity of CO_2 results in "in-situ" seeding
  - Subsonic/transonic condensation known to produce larger particles
  - Pre-cooling challenged by conversion of captured CO_2 kinetic energy to heat

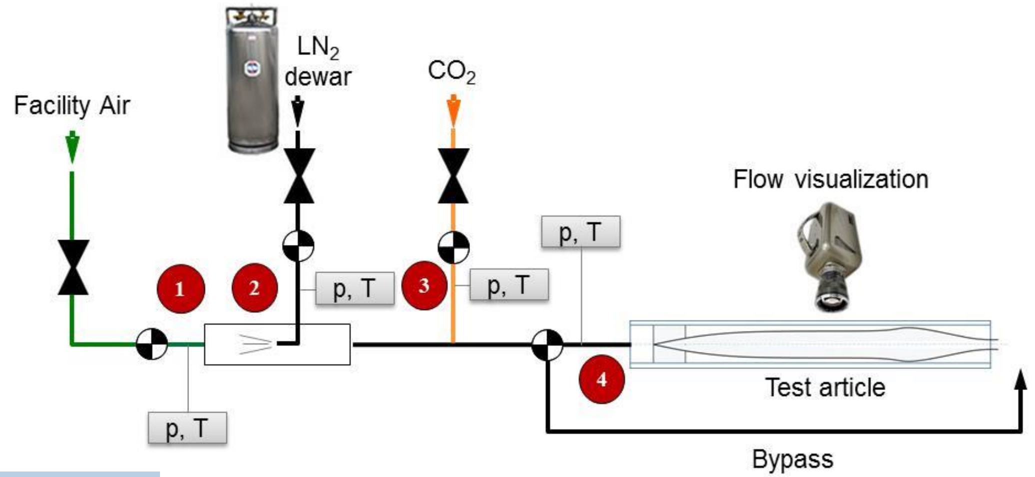
Updated System Schematic and Trade Results

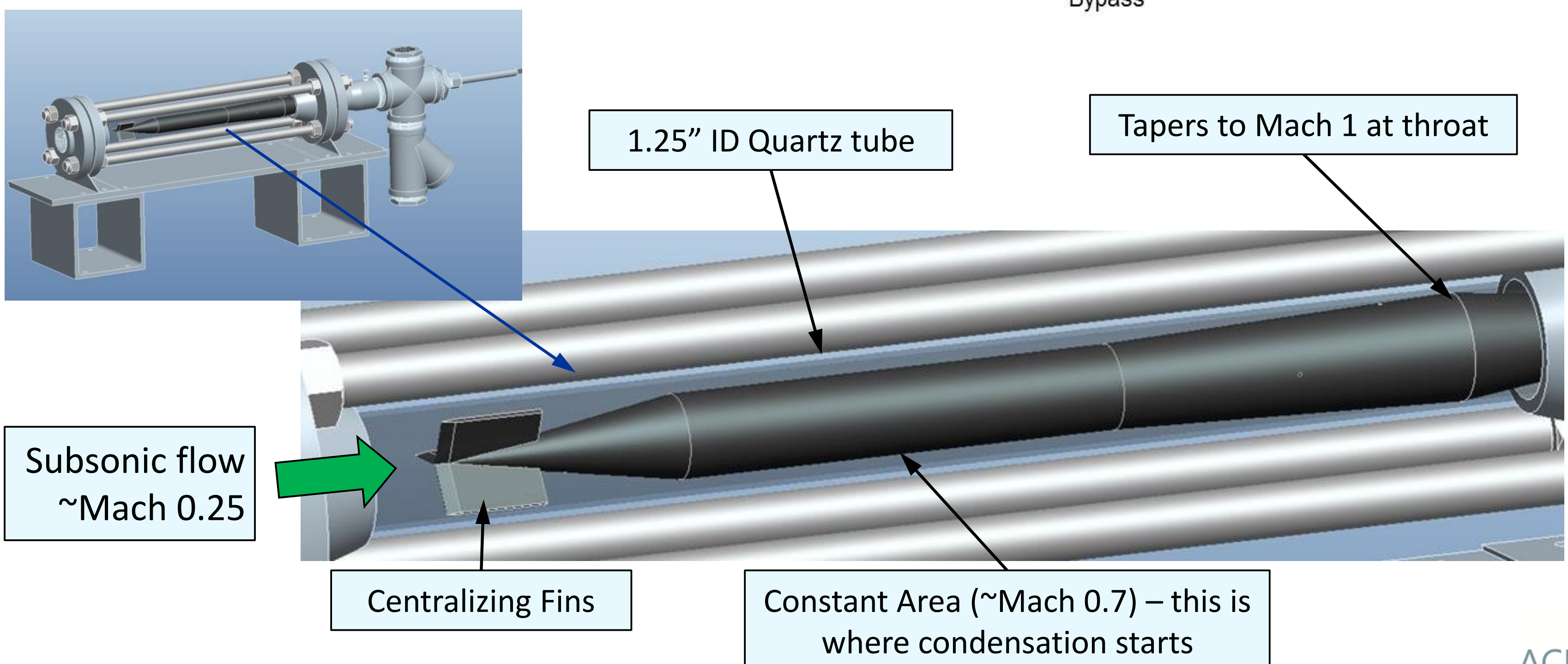


CASE		A	B	C	D	E	F	G	H	I	J
T ambient	C	15	15	15	15	15	15	5	-5	5	-5
KE converted to heat in CO2 stream	%	0%	50%	100%	50%	50%	100%	50%	50%	50%	50%
Dilution	%	0%	0%	0%	50%	100%	50%	50%	50%	100%	100%
Compressor pressure ratio PR		6.9	8.2	10	5.0	3.6	5.2	4.8	4.47	3.8	3.6
Compressor Power	kJ/kg_tot	251	281	316	254	254	262	236	216	235	219
Impulse Turbine Power	kJ/kg_tot	-36.1	-20.0	0.0	-12.4	-9.0	0.0	-11.7	-11.0	-8.5	-7.9
V at capture plane	m/s	597	628	669	607	597	616	589	570	578	560
Delta Tsat upstream of ICES Nozzle	C	**-2**	15	38	52	71	57	42	33	61	52

Current Focus on Subsonic Test Article

Orbital ATK





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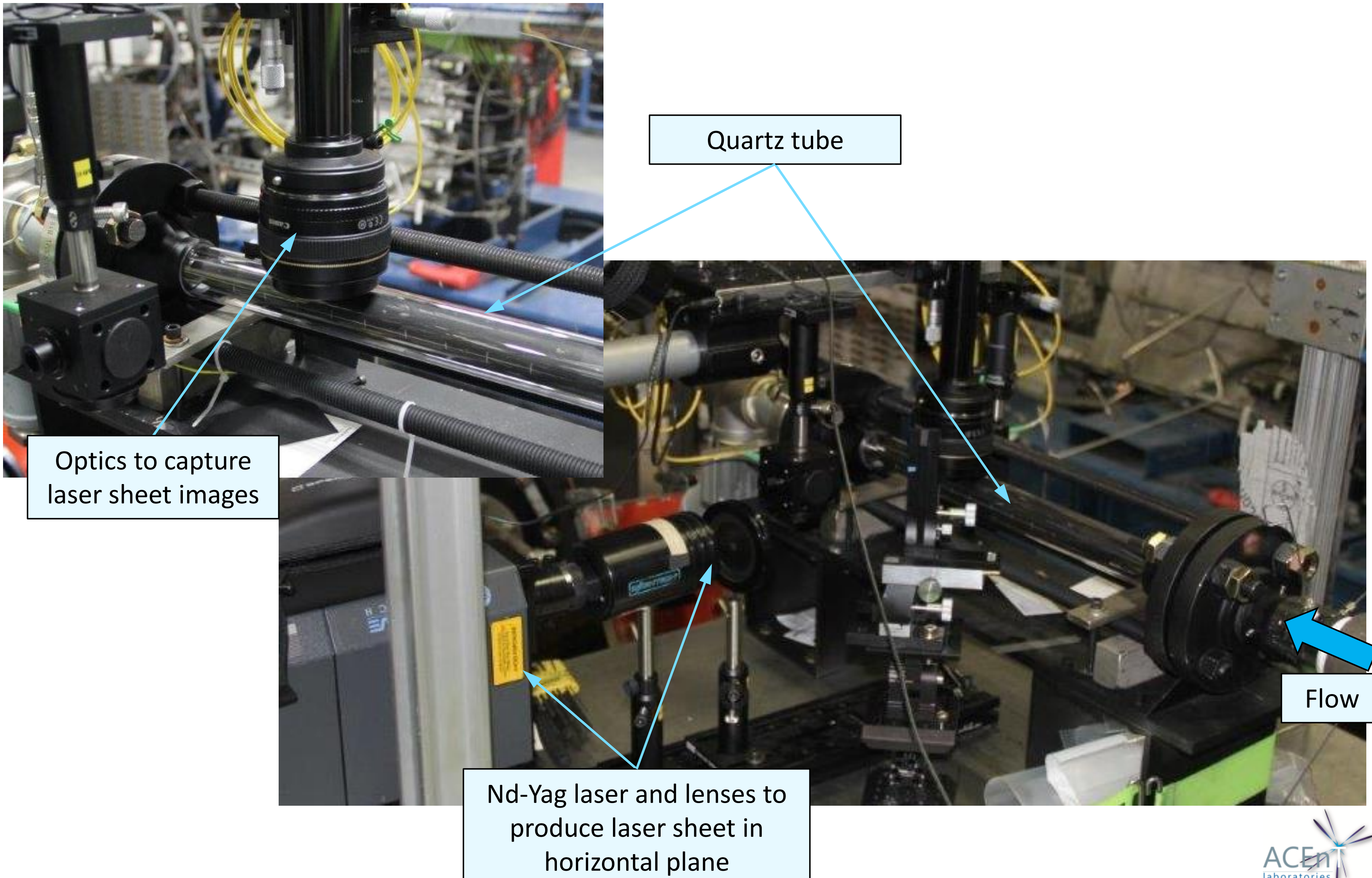
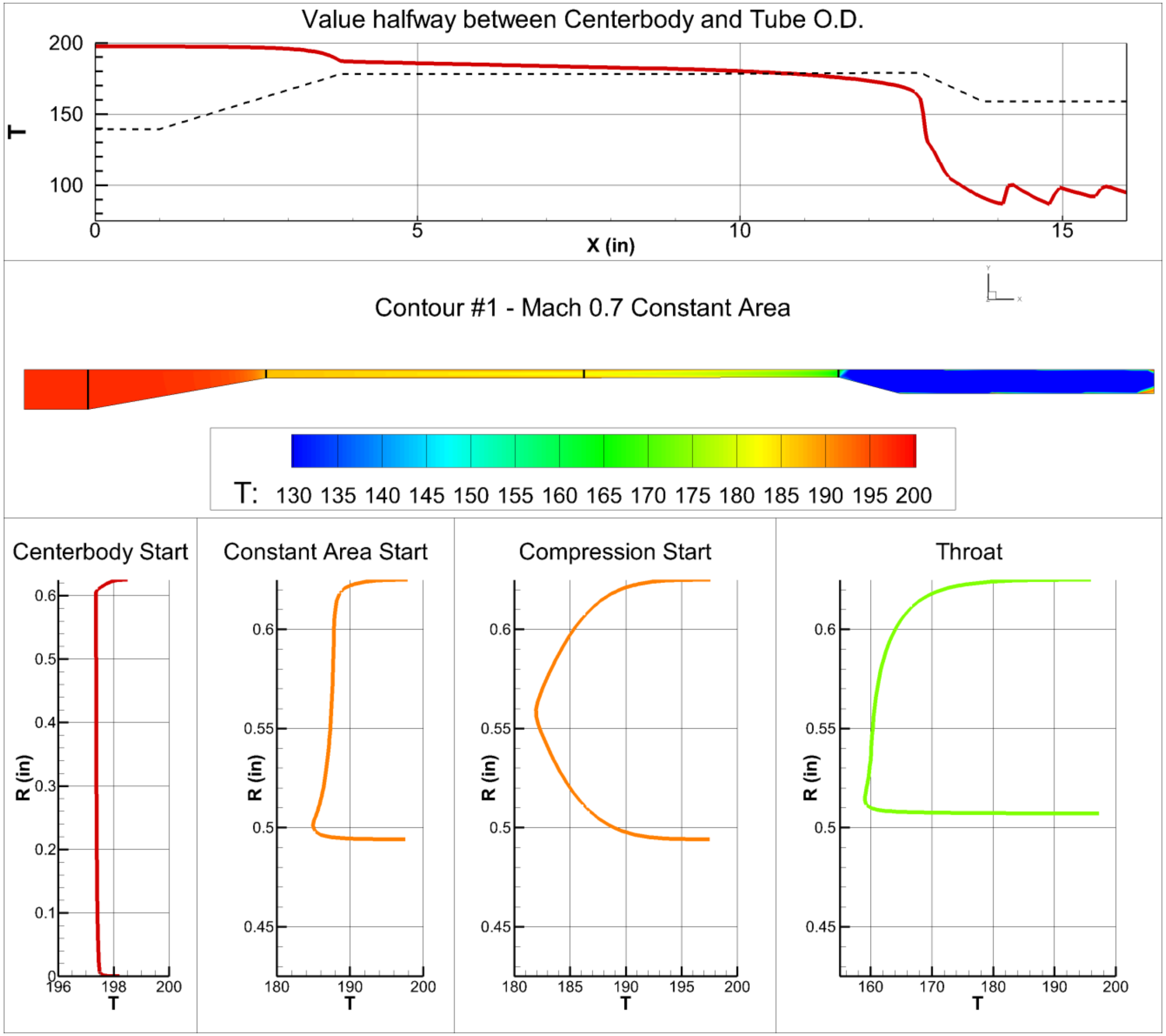
Test Article in Orbital ATK Lab



CFD Results - Temperature

Orbital ATK



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ICES Economic Impact

Orbital ATK

- 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

- Updated process conditions have been provided to EPRI and WP and an updated TEA is in progress
- Anticipate cost per tonne of CO_2 captured >$50 tonne due to increased compression requirements

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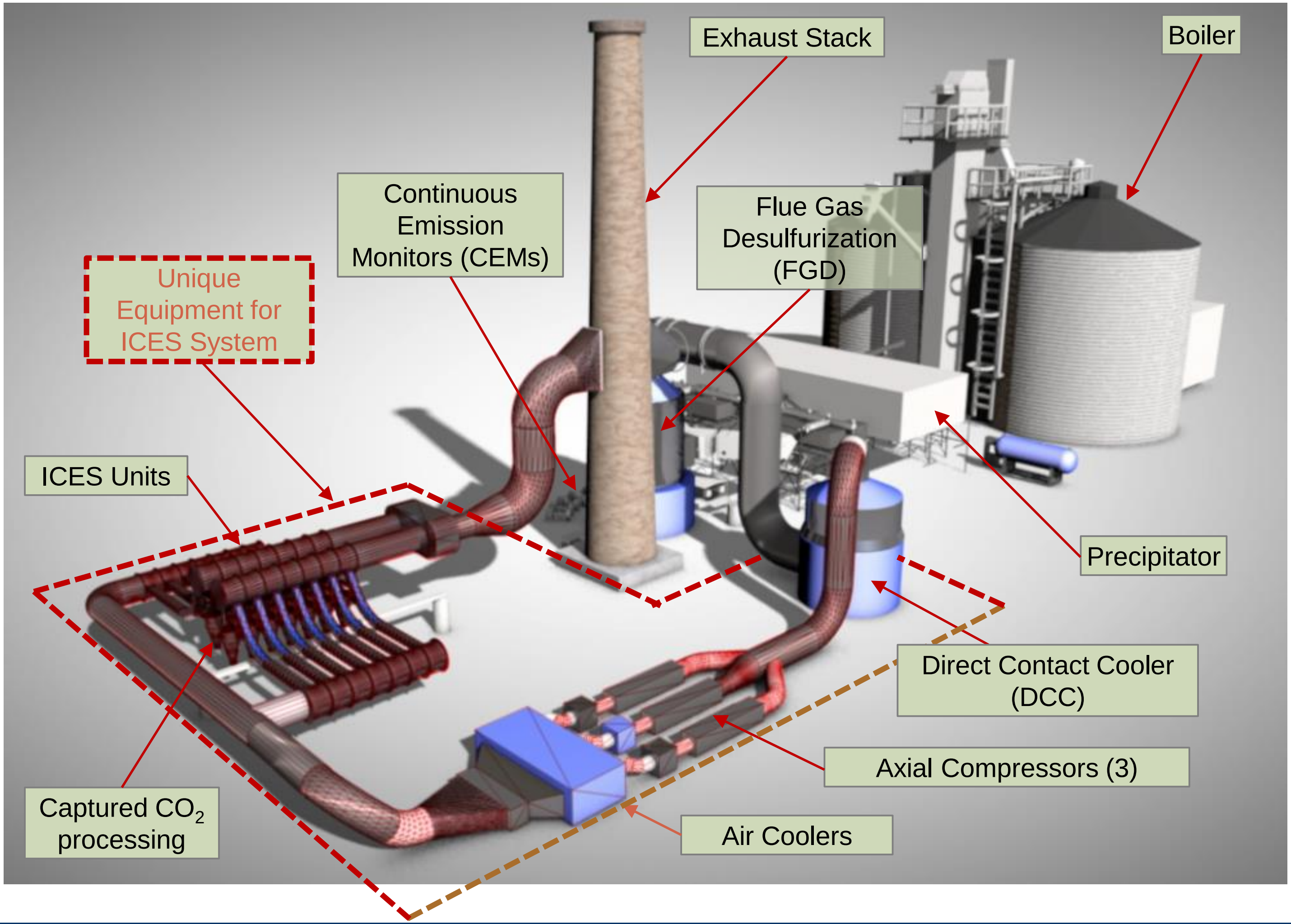
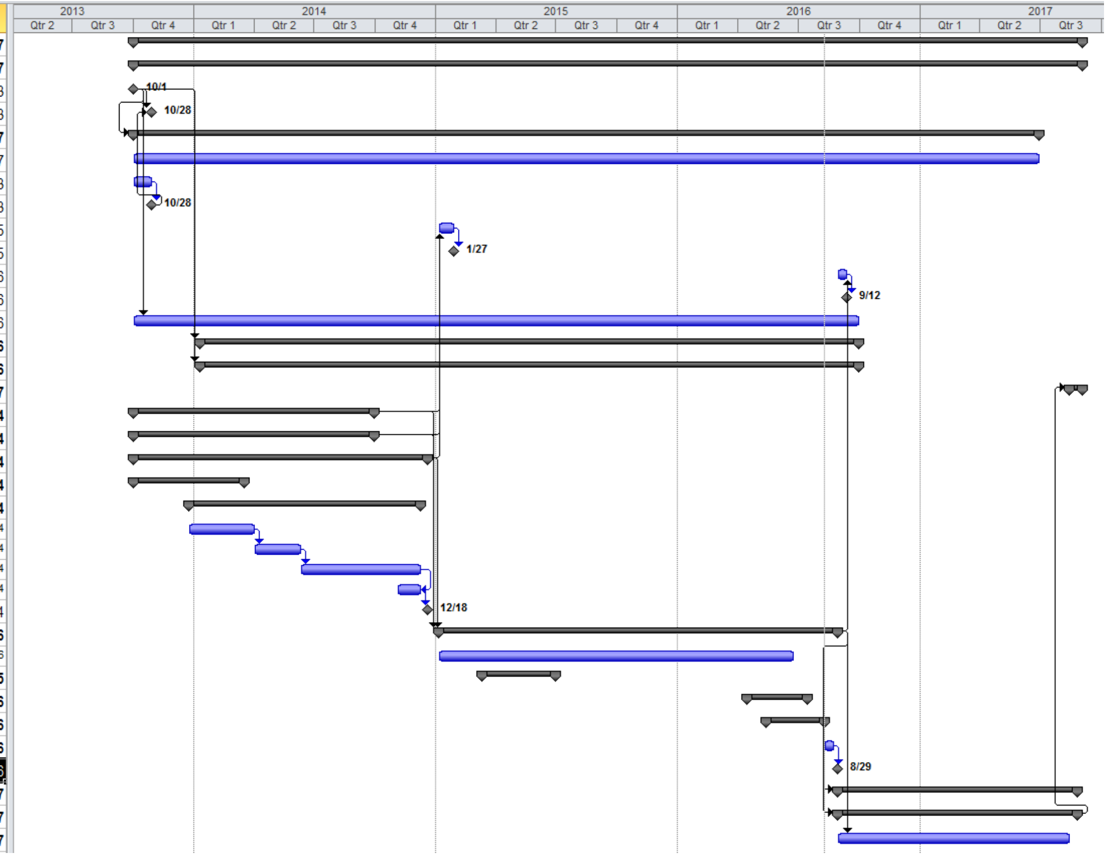
ICES Plant Layout and Footprint



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

WBS	Task Name	Start	Finish
1	NETL-ICES Development Program	10/1/13	9/1/17
1.1	Program Management	10/1/13	9/1/17
A	Authorization to Proceed	10/1/13	10/1/13
1.1.1	MS 2: Kickoff Meeting	10/28/13	10/28/13
1.1.2	Program scope, schedule and budget tracking	10/1/13	6/29/17
1.1.2.1	Earned value tracking	10/1/13	6/29/17
1.1.2.2	Update Budget Period 1 Project Management Plan (PMP)	10/1/13	10/28/13
1.1.2.3	MS1: Updated BP1 PMP complete	10/28/13	10/28/13
1.1.2.4	Update Budget Period 2 Project Management Plan (PMP)	1/5/15	1/27/15
1.1.2.5	MS4: Updated BP2 PMP complete	1/27/15	1/27/15
1.1.2.6	Update Budget Period 3 Project Management Plan (PMP)	8/29/16	9/12/16
1.1.2.7	MS6: Updated BP3 PMP complete	9/12/16	9/12/16
1.1.3	Risk Identification, assessment and mitigation planning	10/1/13	9/29/16
1.1.4	Quarterly Reporting and Reviews	1/10/14	9/30/16
1.1.5	Technical Reviews	1/10/14	9/30/16
1.1.6	Final Report	8/14/17	9/1/17
1.2	Lab-scale Condensation/Growth Investigations	10/1/13	9/29/14
1.3	Analytical and Computational Investigations	10/1/13	9/29/14
1.4	Bench-scale Capture and Diffuser Testing	10/1/13	12/18/14
1.4.1	Capture duct (with solid CO2 injection)	10/1/13	3/17/14
1.4.2	Diffuser Characterization	12/24/13	12/8/14
1.4.2.1	Design Hardware	12/24/13	3/31/14
1.4.2.2	Fab and Install Hardware	4/1/14	6/9/14
1.4.2.3	Test	6/10/14	12/8/14
1.4.2.4	Analyze Data and Benchmark CFD	11/4/14	12/8/14
1.4.3	MS3: Capture Duct / Diffuser demonstration complete	12/18/14	12/18/14
1.5	Bench-scale Condensation/Growth Testing	1/5/15	8/29/16
1.5.1	Instrumentation Updates	1/5/15	6/23/16
1.5.2	CFD and Condensation Modeling	3/11/15	6/30/15
1.5.3	Subsonic Condensation ICES Analysis and Design	4/15/16	7/14/16
1.5.4	Subsonic Condensation ICES Testing	5/13/16	8/9/16
1.5.5	Test additional conditions as needed	8/9/16	8/23/16
1.5.6	MS5: Bench scale condensation/growth testing complete	8/29/16	8/29/16
1.6	Integrated System	8/29/16	8/25/17
1.7	Technoeconomic Analysis (TEA) and EH&S Assesssment	8/29/16	8/25/17
1.8	Commercialization Pathways	8/29/16	8/14/17



MS 1. Updated BP1 PMP – **complete**

MS 2. Kickoff meeting - **complete**

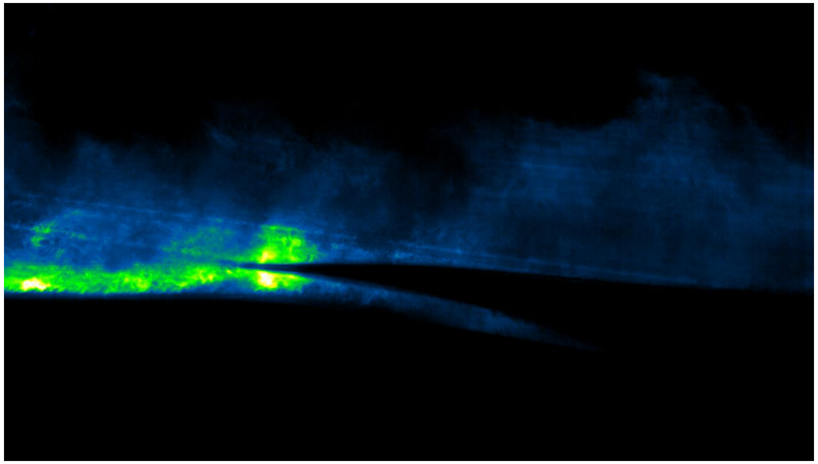
MS 3. Capture duct/diffuser demonstration – **complete**

MS 4. Updated BP2 PMP – **complete**

MS 5: Bench scale condensation/growth testing – **planned 8/29/2016**

Summary

- ICES Technology continues to prove challenging but still holds promise as an alternative to adsorbents and membranes
- Current NETL effort focused on solving key technical challenge of particle size
  - Re-baselined program plan includes pre-cooling of flue gas using captured CO_2 "cold sink" to enable some subsonic condensation
  - Update to techno-economic analysis in progress



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- **NYSERDA**
- **NYS-DED**