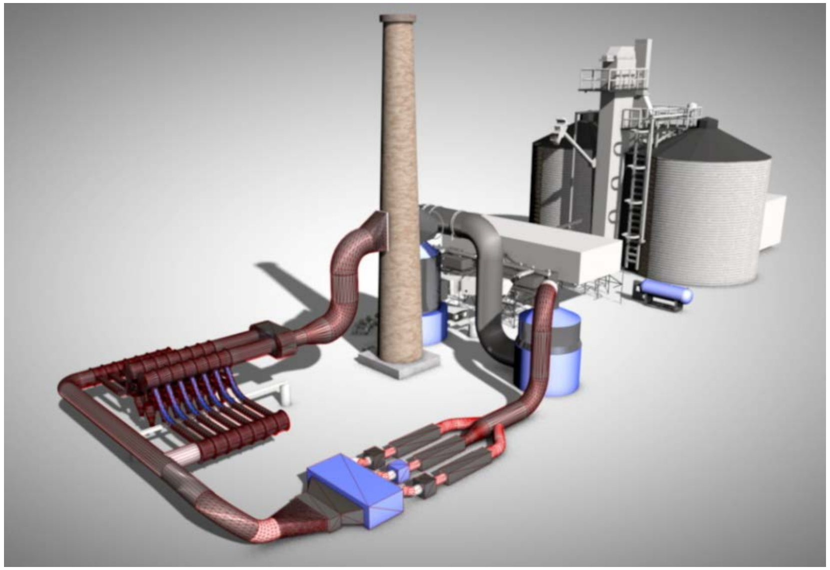
Supersonic Post-Combustion Inertial CO_2 Extraction System

Kickoff presentation to NETL

Contract # DE-FE0013122

Pittsburgh, PA

November 14, 2013



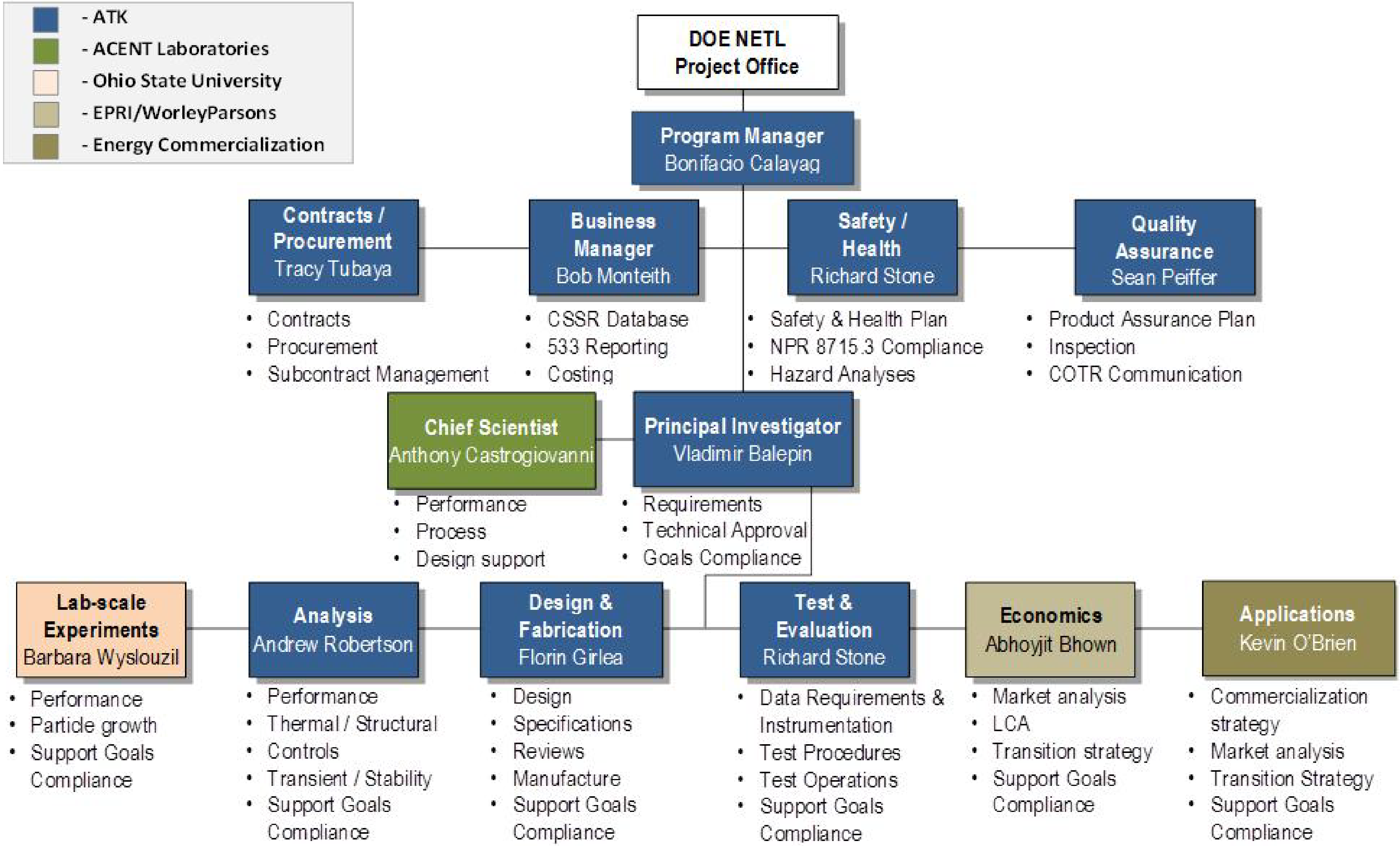
Objectives of the kickoff meeting

- **To provide an overview of ICES including past work and results**
- **To discuss our proposed plans for the current effort in the context of how we will address the key remaining challenges**

Presentation Outline

- Team overview and introductions
- Overview of ICES concept
- Review of results from ARPA-E IMPACCT program activity
- Summary of challenges and risks remaining
- Overview of our plans for this effort
- SOPO/PMP and milestone review
- Summary and Q&A

ICES Team Organization



- 🟦 - ATK
- 🟩 - ACENT Laboratories
- ⬜ - Ohio State University
- 🟨 - EPRI/WorleyParsons
- 🟫 - Energy Commercialization

DOE NETL Project Office

Program Manager
Bonifacio Calayag

Contracts / Procurement
Tracy Tubaya
- Contracts
- Procurement
- Subcontract Management

Business Manager
Bob Monteith
- CSSR Database
- 533 Reporting
- Costing

Safety / Health
Richard Stone
- Safety & Health Plan
- NPR 8715.3 Compliance
- Hazard Analyses

Quality Assurance
Sean Peiffer
- Product Assurance Plan
- Inspection
- COTR Communication

Chief Scientist
Anthony Castrogiovanni
- Performance
- Process
- Design support

Principal Investigator
Vladimir Balepin
- Requirements
- Technical Approval
- Goals Compliance

Lab-scale Experiments
Barbara Wyslouzil
- Performance
- Particle growth
- Support Goals Compliance

Analysis
Andrew Robertson
- Performance
- Thermal / Structural
- Controls
- Transient / Stability
- Support Goals Compliance

Design & Fabrication
Florin Girlea
- Design
- Specifications
- Reviews
- Manufacture
- Support Goals Compliance

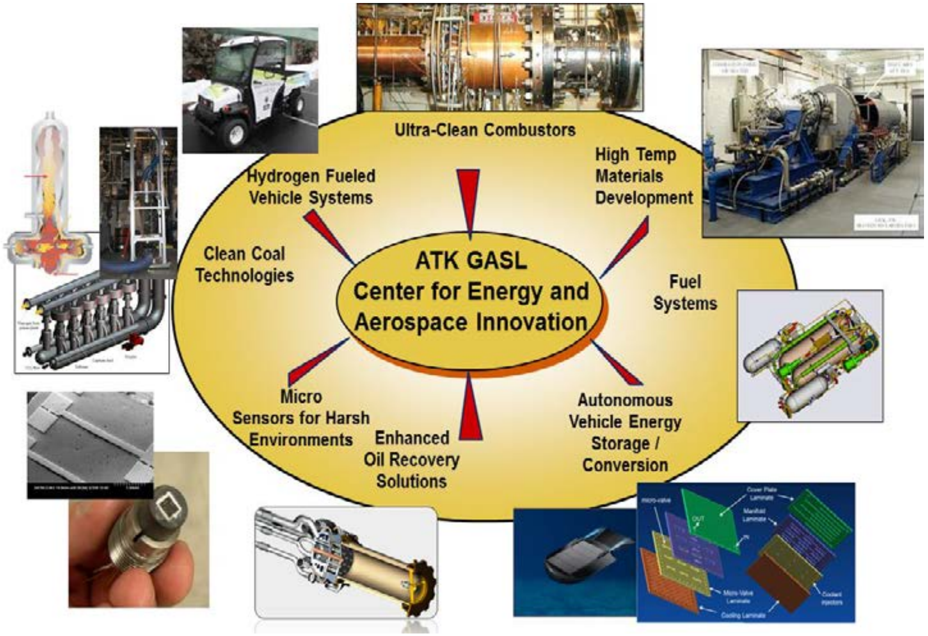
Test & Evaluation
Richard Stone
- Data Requirements & Instrumentation
- Test Procedures
- Test Operations
- Support Goals Compliance

Economics
Abhoyjit Bhown
- Market analysis
- LCA
- Transition strategy
- Support Goals Compliance

Applications
Kevin O'Brien
- Commercialization strategy
- Market analysis
- Transition Strategy
- Support Goals Compliance

Company Backgrounds - ATK and ACENT

- ATK is a leading aerospace & defense contractor
- ATK GASL in Ronkonkoma, NY operates the ATK Center for Energy and Aerospace Innovation
- Expertise and research interests include :
  - Aerospace propulsion
  - Carbon capture
  - Hydrogen fueled vehicles
  - Clean coal technologies
  - Oil recovery solutions



- ACENT is a small business dedicated to applying expertise in aerospace and defense to clean energy challenges
- Founded in 2007, ACENT is developing technologies in CO_2 capture, algal biomass, hydrogen vehicles, and enhanced oil recovery

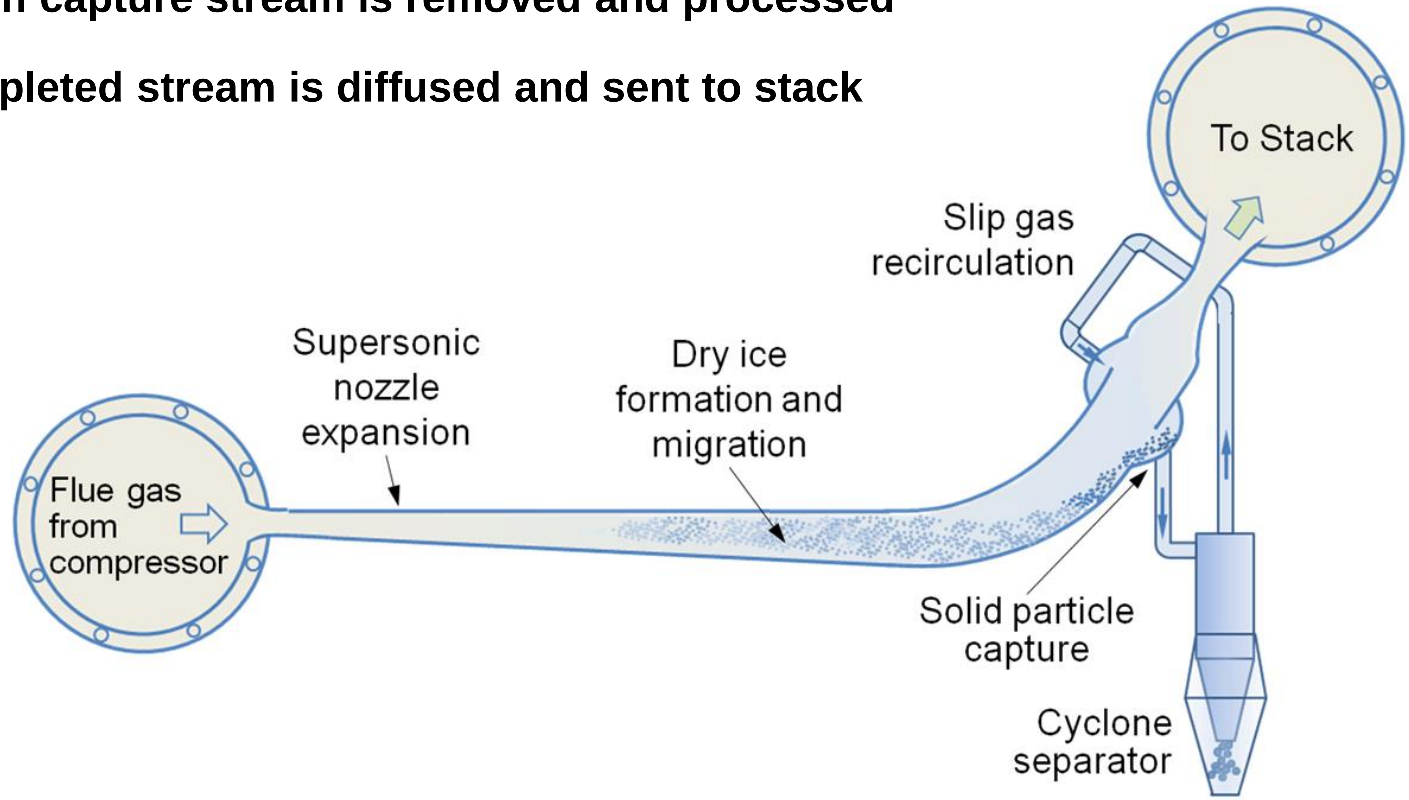
- ICES utilizes some methods developed under a DOE SBIR with ACENT

Other Key Team Members

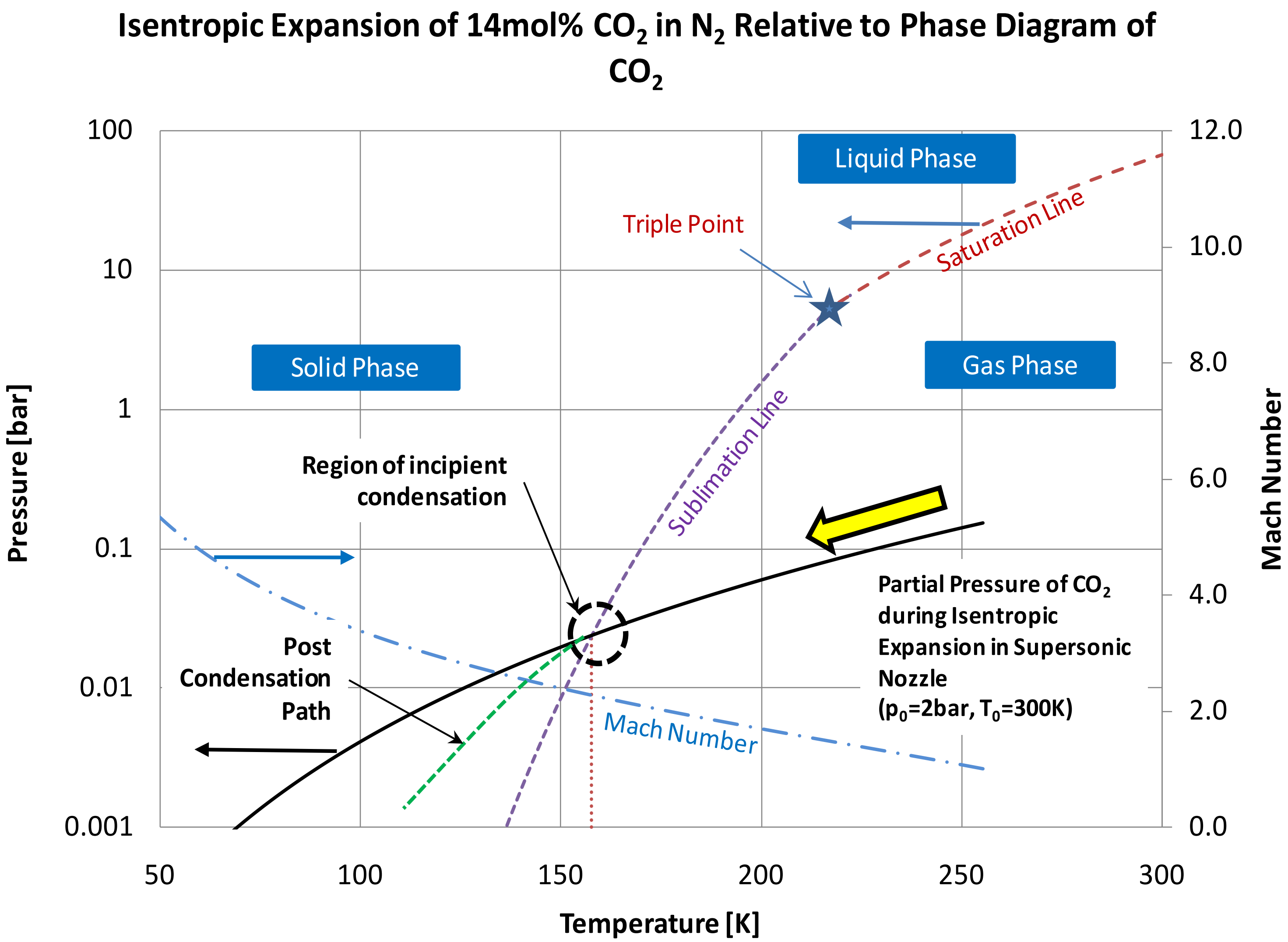
Team Member	Background	Role in the Program
Ohio State University	Department of Chemical and Biomolecular Engineering has over 20 years experience working in the area of aerosol physics and chemistry, focusing on the formation, growth, and structure of nanodroplets. Supersonic nozzles are at the heart of the experimental apparatus used in all of this work.	• Support of the analytical study • Lab-scale experiments
EPRI	EPRI has extensive knowledge and contacts in the electric power industry provide a perspective to prepare technical and economic evaluations of the capture system in a broader electric power industry setting, and in the context of competing CO_2 capture technologies.	• Techno-economic analysis • Cost-share partner
WorleyParsons	WP has more than 100 years of power experience having designed, constructed or managed the construction of more than 595 power generation plants. WP is proven and recognized industry leader in carbon management.	• Techno-economic analysis support
Energy Commercialization	EC is dedicated to enabling energy projects by transitioning bench-scale systems through pilot testing, demonstration, and then full deployment. Its mission is to assist organizations in enhancing energy security and managing and reducing carbon emissions	• Commercialization pathway development

ICES Overview

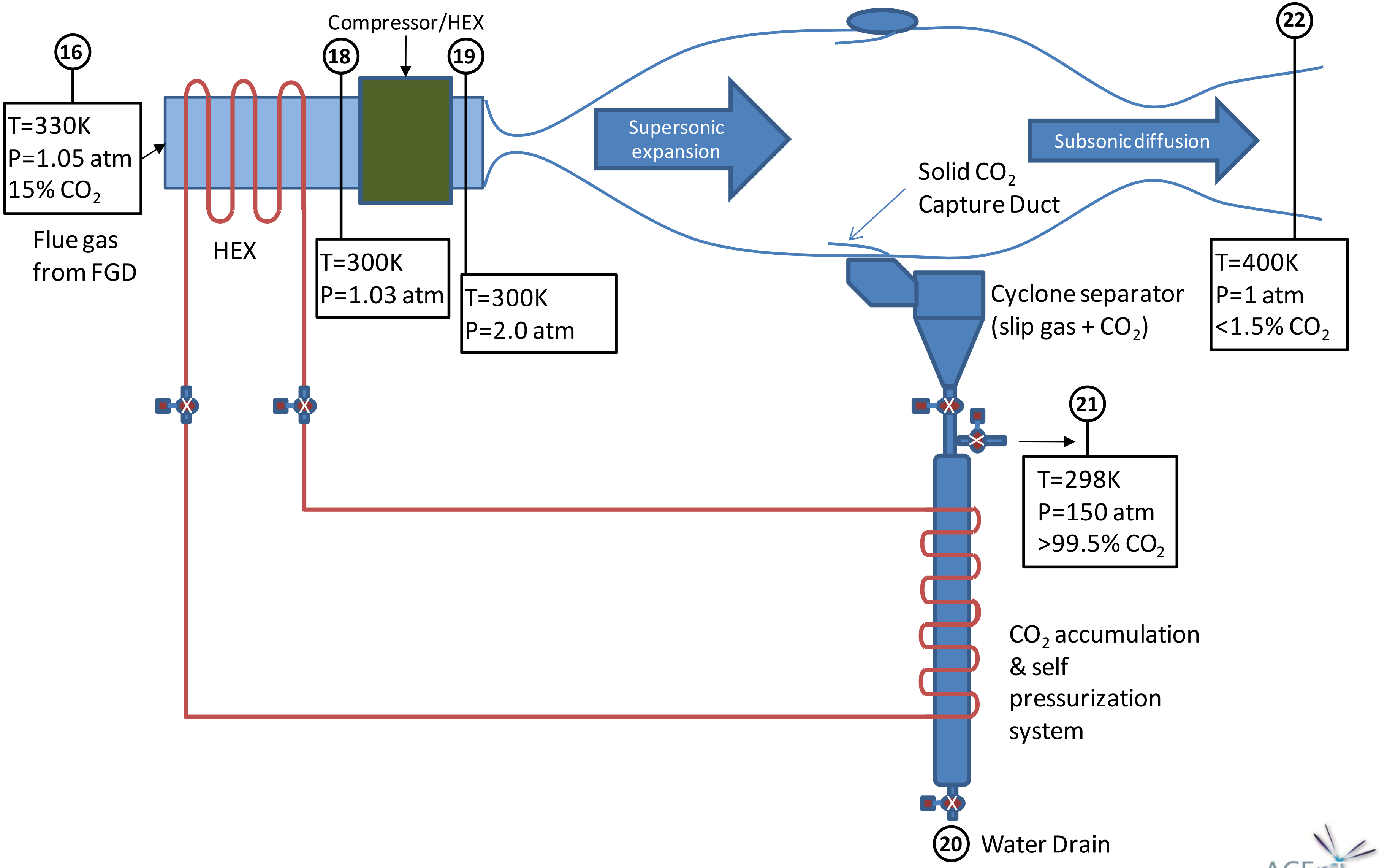
- **Supersonic expansion of compressed flue gas results in CO_2 desublimation (high velocity → low p & T)**
- **Inertial separation of solid particles instigated by turning the supersonic flow**
- **CO_2-rich capture stream is removed and processed**
- **CO_2-depleted stream is diffused and sent to stack**



Thermodynamics of ICES on a P-T Diagram



Some key numbers for reference



Key Advantages of ICES over other options

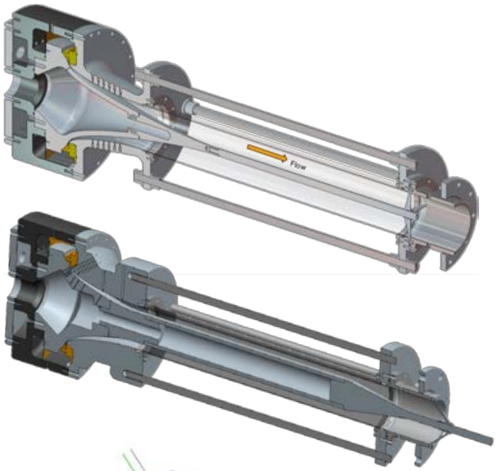
- No moving parts (after start)
- No chemicals/additives or other consumable media
- No refrigeration expense – low temperatures from supersonic expansion
- Inexpensive construction (concrete, sheet metal)
- Small footprint
  - ICES units in test are equivalent to 250-500kW slip stream
  - The latest unit (250kW) is 96” x 24” x 3”
- Small size enables distributed deployment for other process applications in the petroleum and chemical industries
- Availability of “cold sink” in solid CO_2 accumulated

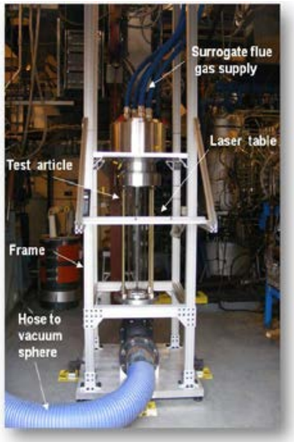
ICES Development Challenges

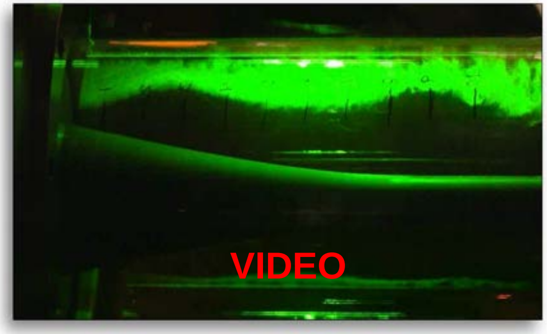
- Development of optimized supersonic contour to maximize particle size/migration and minimize pressure losses
- Minimization of “slip gas” that is removed with solid CO_2
- CO_2 purity unknowns - other flue gas impurities that condense will be removed with the CO_2
- Solid CO_2 management/self pressurization
- This really is rocket science….but once the design is complete, it is easy and inexpensive to build and operate

Summary of test activity under IMPACCT

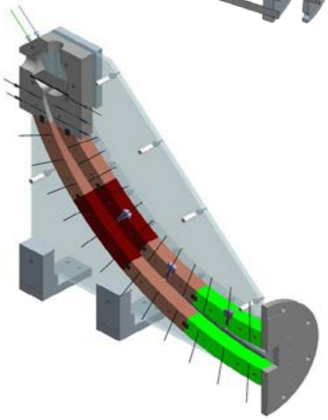
Gen1a and 1b (swirl)

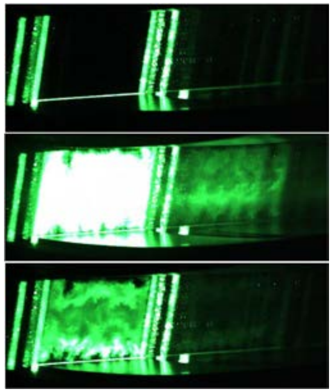




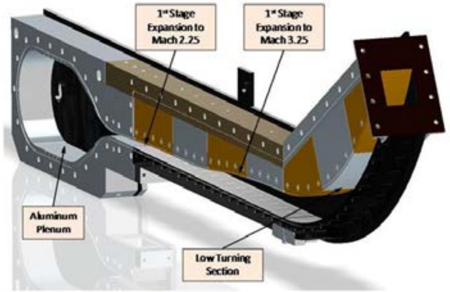


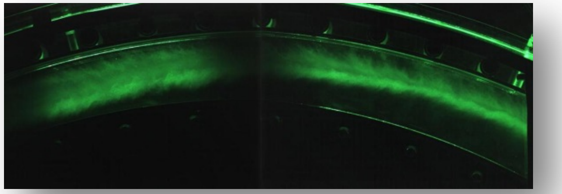
Gen2 (2D)





Gen3 (2D - long)

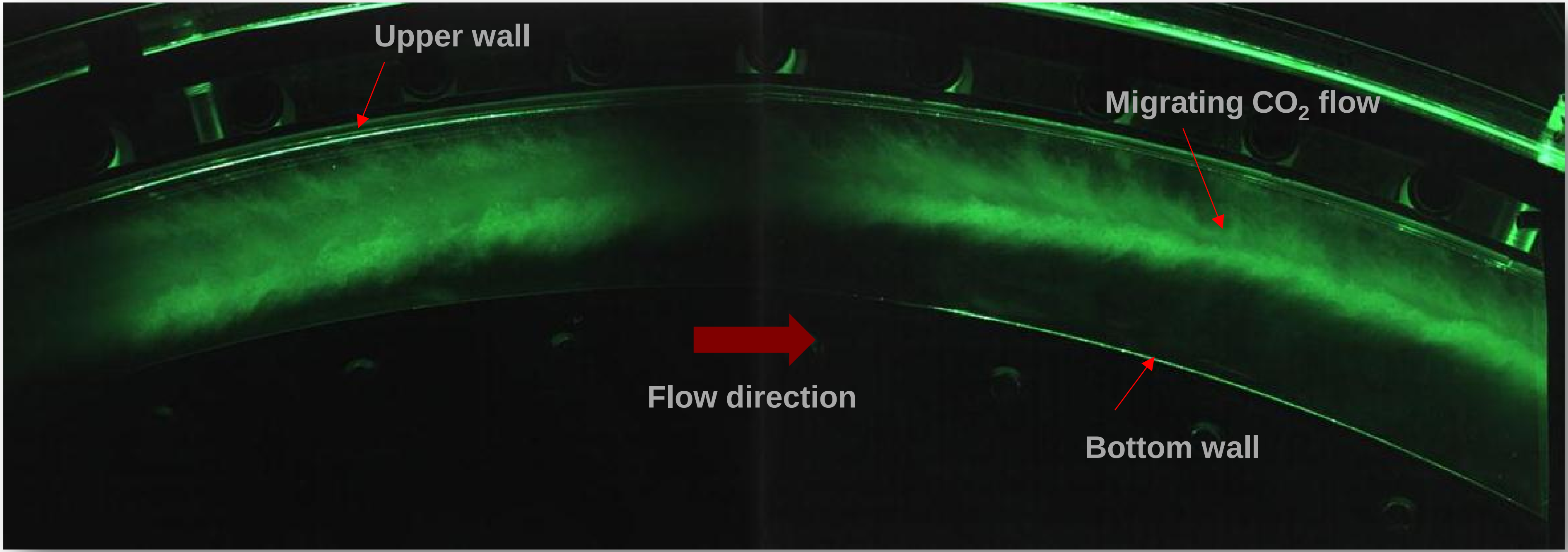




ICES Unit Illuminated With Laser Sheet

3000 lb/hr flow unit, equivalent of ~0.3MW power

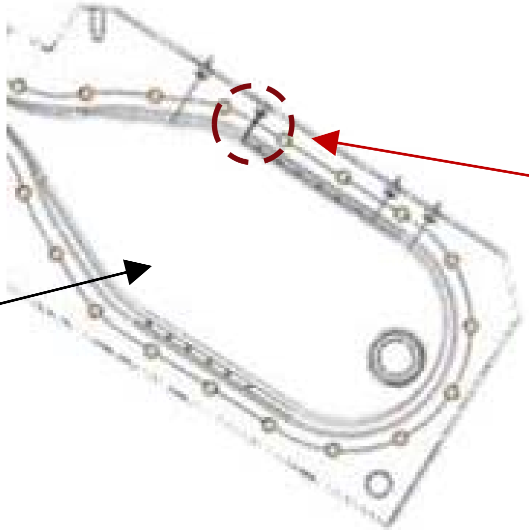
Representative Laser Sheet Image



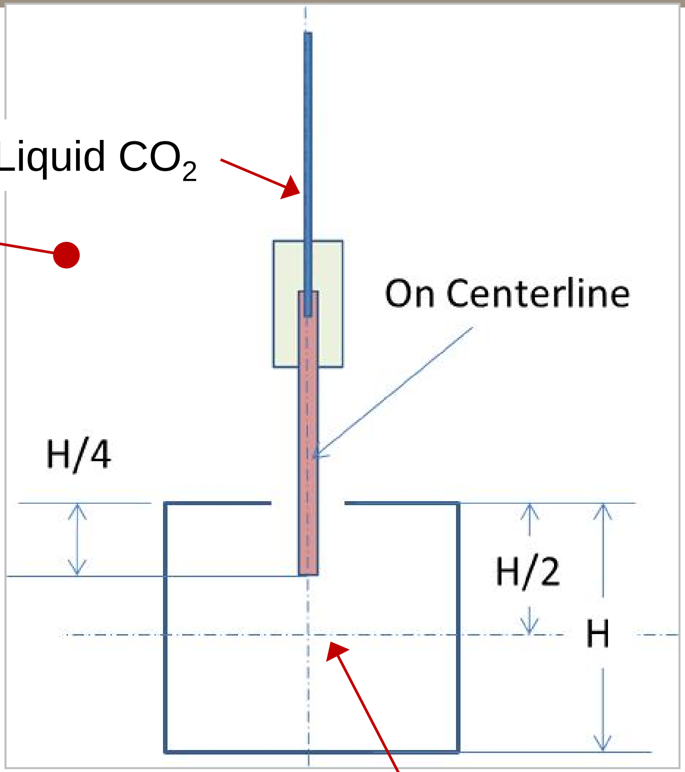
Splice of images 601-68 and 602-33

Tests were conducted at nominal conditions (Pc=30 psia, 20%wt CO_2) with pressure variation to 70 psi and concentration variation to 30%wt. Apparent migration of the CO_2 stream towards upper wall was observed. Near duct exit white solid CO_2 stream occupied ~50% of the duct height.

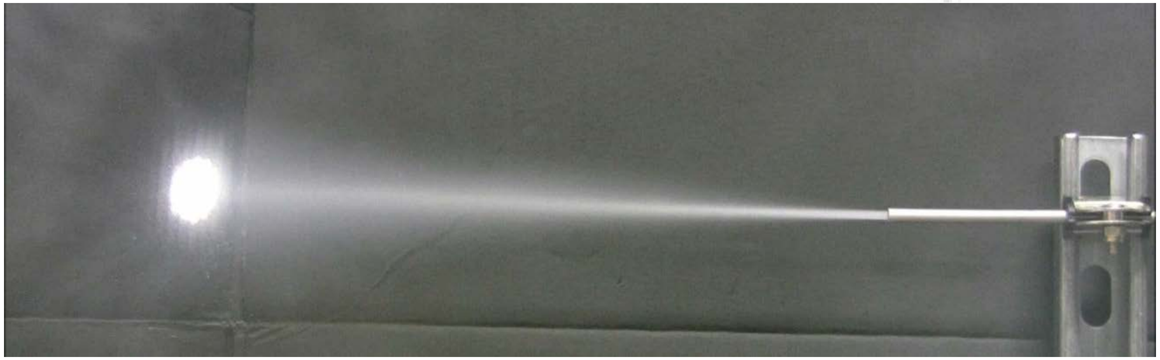
CO_2 Particle Injection in Plenum



ICES inlet manifold



CO_2 particles



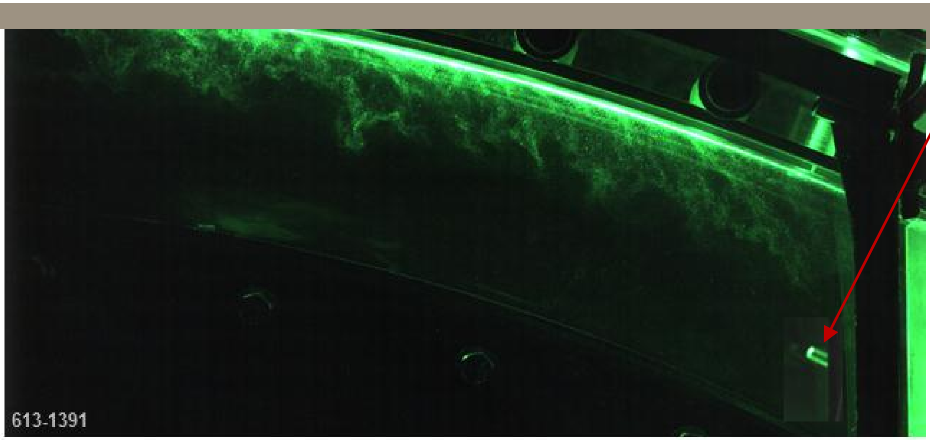
Shroud injector based on AFIT design and results

CO_2 particle injection at ~10+ micron SMD at ~5% of the total flow was arranged in order to:

1) Observe migration of these particles and
2) Promote agglomeration with particles formed from main CO_2 flow

CO_2 Particle Injection Results

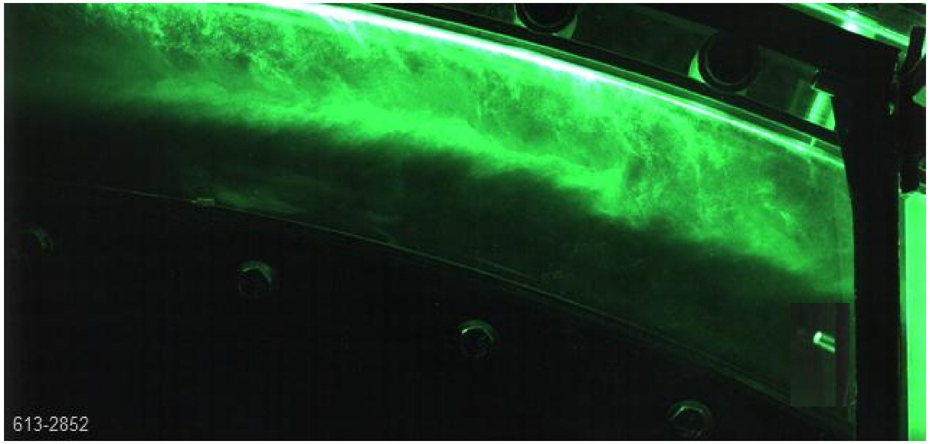
a. Air+5% “liquid” CO_2



GC probe reading: **0% CO_2**

Image: bright layer at the upper wall, individual particles are seen in the near upper wall flow (see next chart)

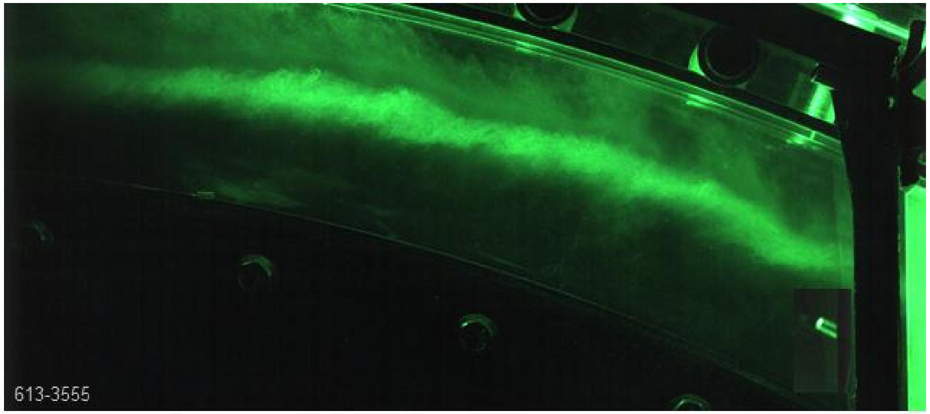
b. Air+5% “liquid” CO_2 +20% gaseous CO_2



GC probe reading: ~20% CO_2

Image: very bright layer at the upper wall, individual particles are seen in the near upper wall flow

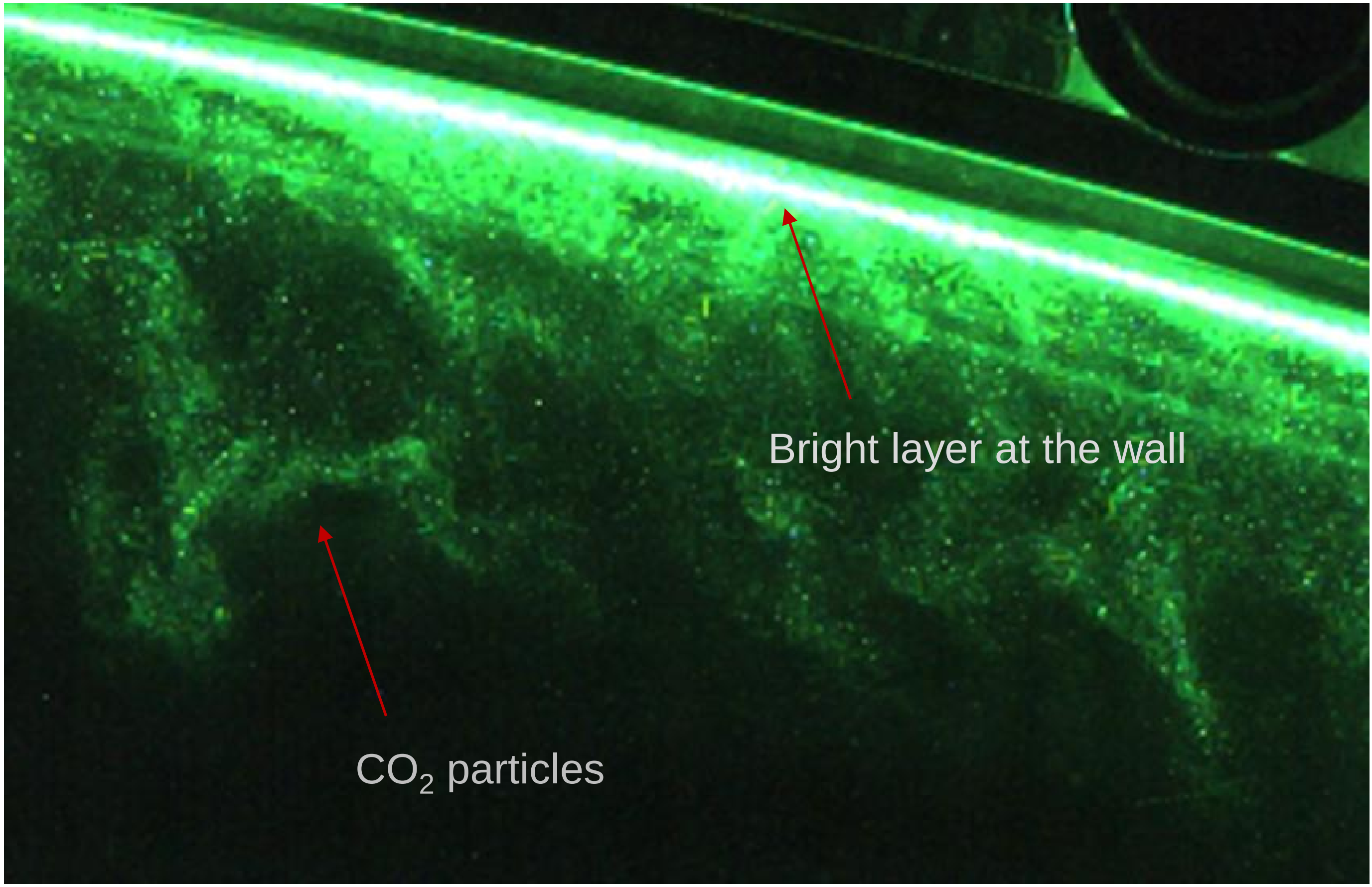
c. Air+20% gaseous CO_2



GC probe reading: ~20% CO_2

Image: some migration is visible

CO_2 Particle Injection Results - Flow structure

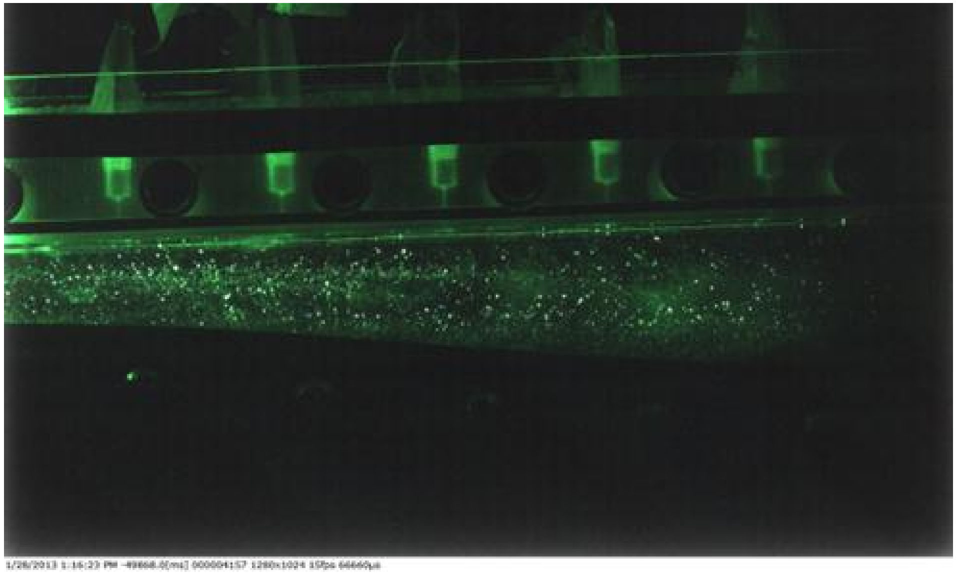


Region of future capture duct

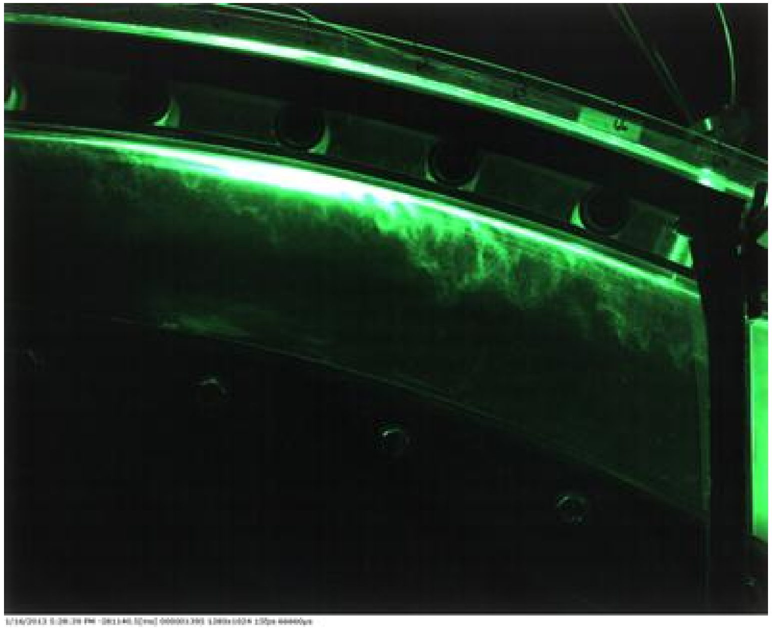
Conclusion:
When reasonably large particles are present in the flow, they migrate rather close to the upper wall - particle growth strategy focus of current activity

Results and Further Plans (CO_2 particle injection)

- The most important result is that migration of 10+ micron CO_2 particles was demonstrated
- Migration occurs only in the turning duct
- Particles did not interact with gaseous and solid CO_2 (too few particles?)
- Particles appeared to be too big to promote agglomeration
- For the current phase of the study, generation of smaller particles is planned (~2-3 microns)



Particles do not favor top or bottom wall in the upstream (un-turned) flow



Particles migrate to the top wall in the turning duct

ICES Economic Impact (WP analysis)

A preliminary Techno-economic assessment by WorleyParsons (WP) determined:

- Cost of electricity (and increase in COE over non-capture case)
- Levelized cost of electricity
- Cost of CO_2 captured
- Cost of CO_2 avoided

WP also evaluated overall efficiency of the different plant configurations. Key efficiency/economic numbers are provided in the table below:

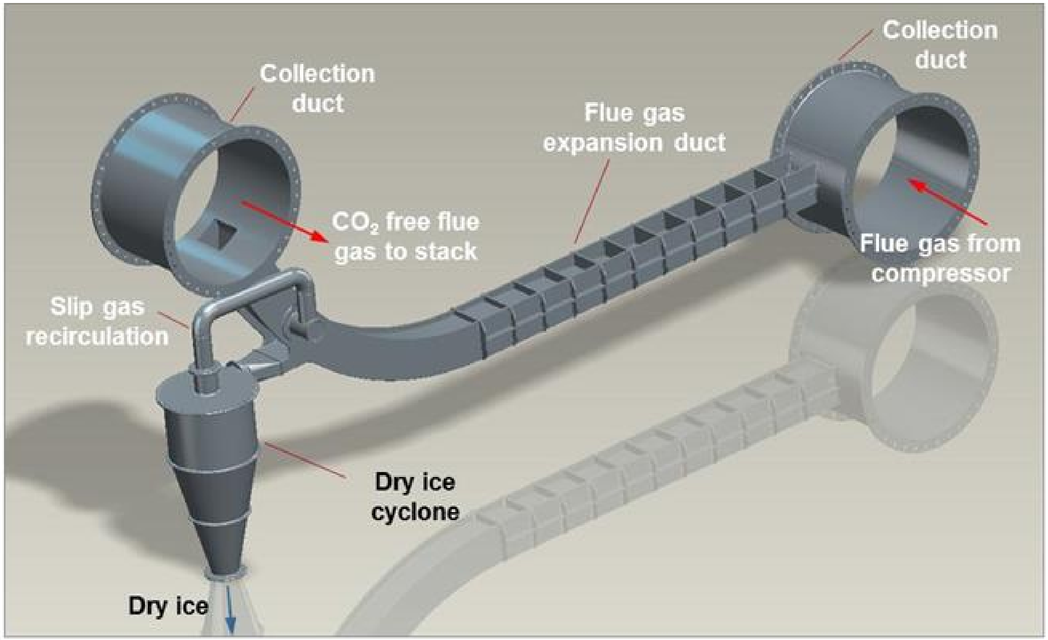
Metric	**Case 11**	**Case 12, Amine Plant**	**ICES Plant**
CO_2 capture	no	yes	yes
Net plant efficiency (HHV basis)	39.3%	28.4%	34.5%
COE % increase	base	77%	42%
Parasitic Load	5.5%	20.5%	7.3%
Cost per ton of CO_2 captured	NA	US$ 62.8	US$ 41.8
Cost per ton of CO_2 avoided	NA	US$ 90.7	US$ 48.4

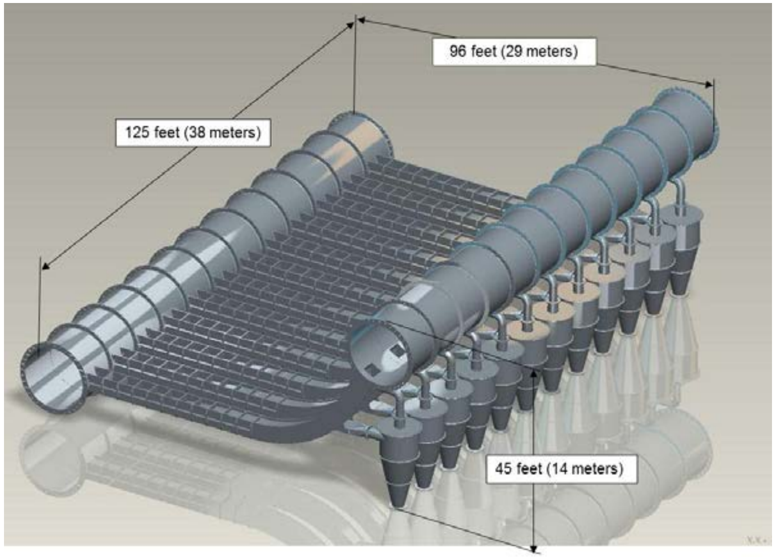
Resulting lower COE increase for ICES technology is based on lower capital and O&M costs and improvements in the overall plant efficiency

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)

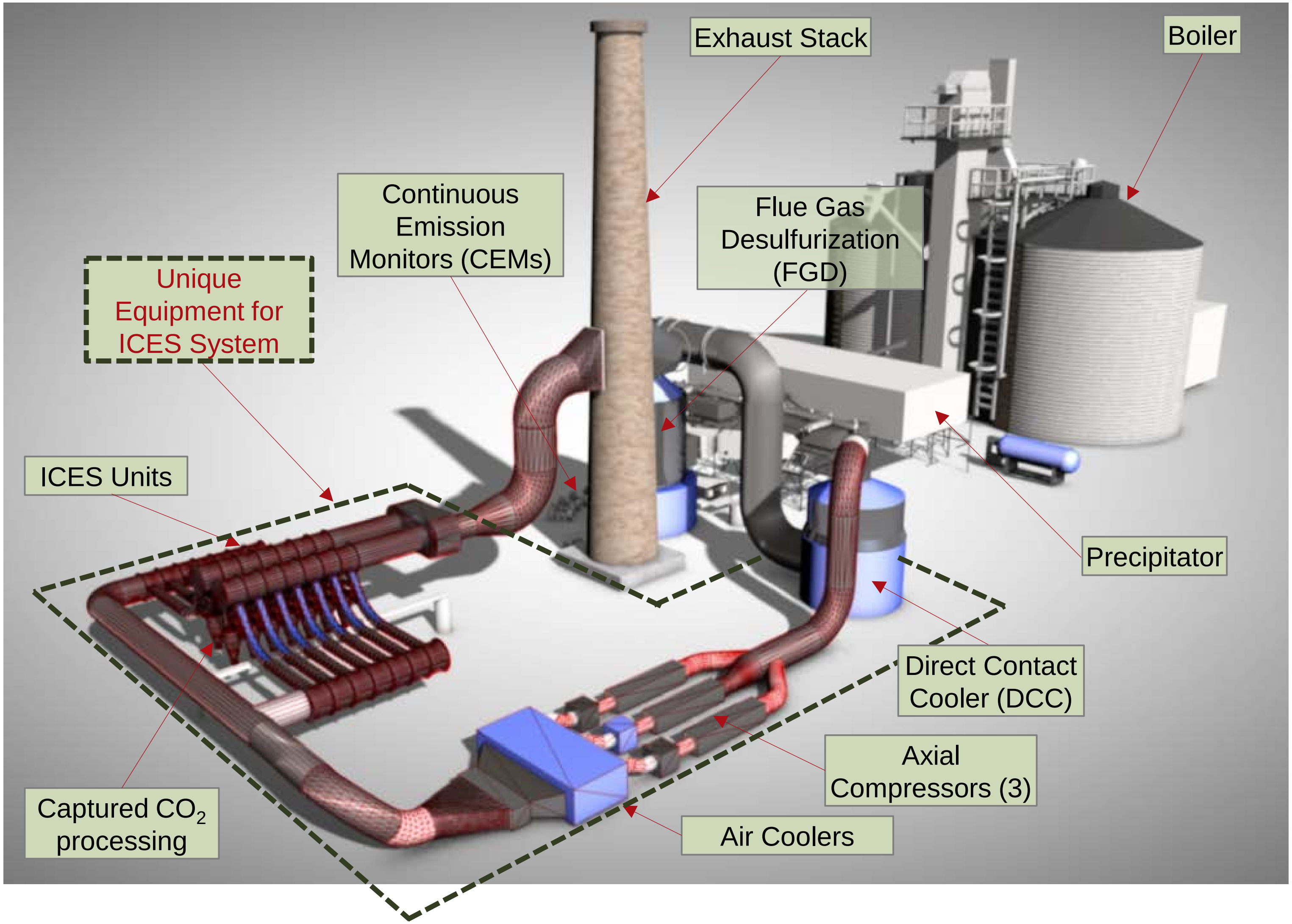
Full Scale ICES Plant Configuration (for 545MW PC plant)

- 545MW power level requires an array of twelve full-scale ICES nozzles
- Modular arrangement allows operation of the system in 1/12th increments of plant power thereby permitting efficient load-following
- The twelve units can be arranged in a one row or in multiple rows. They can also be stacked with other equipment.





ICES Plant Layout and Footprint



The ICES footprint of ~8,000 m^2 compares to 20,000 to 30,000 m^2 for an amine plant of similar capacity. ICES nozzle and compressor stacking can further reduce footprint by 30-40%.

ICES Slipstream Demo Size Comparison

ICES is projected to have a significantly smaller footprint and complexity compared to competing CO_2 capture technologies and hence significantly lower capital and maintenance costs

Amine plant for flow rate equivalent of 0.5MW power

Same 0.5MW capacity ICES unit (does not include compressor and solid CO_2 treatment units)

0.5MW ICES pilot scale comparison to 0.5MW amine pilot at NCCC

Plan of Attack for Current Effort

Three-phase plan addresses the key challenges and risks:

Budget Period 1:

- ✓ Demonstration of solid CO_2 particle growth methods at lab-scale.
- ✓ Demonstration of the separation and capture of migrated particles at bench scale using surrogate controlled CO_2 particle injection.
- ✓ Demonstration of the diffusion of the CO_2-depleted flue gas flow to atmospheric pressure with losses consistent with projected system economics.

Budget Period 2:

- ✓ Bench-scale demonstration of CO_2 particle growth methods supporting particle sizes required for effective migration and separation.

Budget Period 3:

- ✓ Demonstration of the ICES process including condensation, migration, CO_2 removal and diffusion of the CO_2-depleted flue gas flow to atmospheric pressure.
- ✓ Updating the ICES techno-economic analysis showing a path to meeting the DOE carbon capture goals.

Top Level 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
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										🟫	🟫	🟫

Milestone Summary and Tracking

Budget Period	Task or Subtask #	Milestone Number and Description	Planned Completion	Actual Completion	Verification Method
1	1	MS 1. Updated Project Management Plan	10/31/2013	10/28/2013	Project Management Plan document
1	1	MS 2. Kickoff Meeting	12/31/2013	11/14/2013	Presentation held at NETL with electronic copy
1	4	MS 3. Capture duct/diffuser demonstration complete	09/25/2014		Presentation file, Quarterly Report with data summary
2	1	MS 4. Updated Project Management Plan	10/27/2014		Project Management Plan document
2	5	MS 5. Bench scale condensation/growth testing complete	09/23/2015		Presentation file, Quarterly Report with data summary
3	1	MS 6. Updated Project Management Plan	10/26/2015		Project Management Plan document
3	7 and 8	MS 7. Techno-economic analysis (TEA) and EH&S Assessment complete	9/20/2016		TEA and EH&S documents, Quarterly Report
3	6	MS 8. Integrated system testing complete	9/15/2016		Presentation file, Quarterly Report with data summary
3	All	MS 9. Final report complete	12/31/2016		Final report document

Summary

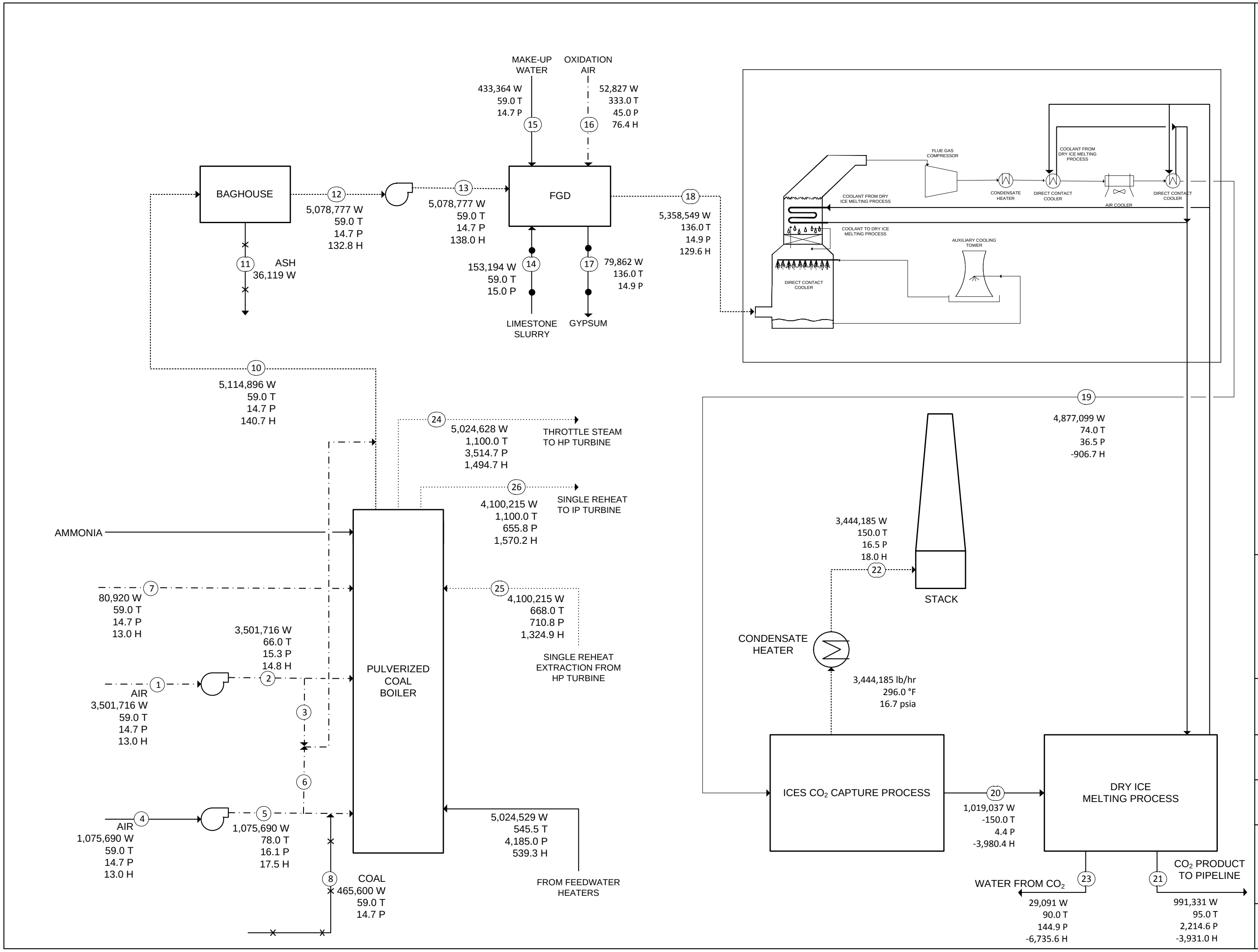
- ICES Technology holds considerable promise as an alternative to adsorbents and membranes
- Preliminary Techno-economic analyses is favorable
- Power plant integration concepts have attractive footprint
- One key technology hurdle remains (particle size) – remaining tasks have less risk
- ARPA-E project has been invaluable to gaining an in-depth understanding of the problem and our solution

BACKUP

Key Assumptions for Economic Analysis

	Case 11 w/o CO$_2$ Capture	**Case 12 w/ CO$_2$ Capture**	**ATK ICES w/ CO$_2$ Capture**
Steam cycle, MPa/°C/°C (psig/°F/°F)	24.1/593/593 (3500/1100/1100)	24.1/593/593 (3500/1100/1100)	24.1/593/593 (3500/1100/1100)
IP/LP turbine crossover duct steam conditions, MPa/°C (psig/°F)	0.93/364 (120/688)	0.40/556 (59/291)	0.93/363 (120/686)
Coal	Illinois No. 6	Illinois No. 6	Illinois No. 6
Condenser pressure, mm Hg (in Hg)	50.8 (2)	50.8 (2)	50.8 (2)
Boiler Efficiency, %	88	88	88
Cooling water to condenser, °C (ºF)	16 (60)	16 (60)	16 (60)
Cooling water from condenser, °C (ºF)	27 (80)	27 (80)	27 (80)
Stack temperature, °C (°F)	57 (135)	32 (89)	66 (150)
SO$_2$ control	Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation
FGD efficiency, % (A)	98	98 (B, C)	98
NOx control	LNB w/OFA and SCR	LNB w/OFA and SCR	LNB w/OFA and SCR
SCR efficiency, % (A)	86	86	86
Ammonia slip (end of catalyst life), ppmv	2	2	2
Particulate control	Fabric Filter	Fabric Filter	Fabric Filter
Fabric filter efficiency, % (A)	99.8	99.8	99.8
Ash distribution, Fly/Bottom	80% / 20%	80% / 20%	80% / 20%
CO$_2$ control	N/A	Econamine	ATK ICES
Overall CO$_2$ capture (A)	N/A	90.2%	90.2%
CO$_2$ sequestration	N/A	Off-site Saline Formation	Off-site Saline Formation

ICES Heat and Material Balance



LEGEND

- ·– · – · – AIR
- –×––×– COAL/ASH
- ········ STEAM
- ········ FLUE GAS

P ABSOLUTE PRESSURE, PSIA
T TEMPERATURE, °F
W FLOWRATE, LBM/HR
H ENTHALPY BTU/LBM

NOTES:

1. ENTHALPY REFERENCE POINT IS NATURAL STATE AT 32°F AND 0.089 PSIA.

PLANT PERFORMANCE SUMMARY

GROSS PLANT POWER:	590 MWe
AUXILIARY LOAD:	40 MWe
NET PLANT POWER:	550 MWe
NET PLANT EFFICIENCY, HHV:	34.5%
NET PLANT HEAT RATE, HHV:	9896 BTU/kW

WorleyParsons
resources & energy

PROJECT:
ATK ICES

HEAT AND MATERIAL
FLOW DIAGRAM

ATK ICES CO_2 CAPTURE CASE
PULVERIZED COAL BOILER AND
GAS CLEANUP SYSTEMS

DRAWING NUMBER:
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Power Plant Steam Cycle with ICES