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A High Efficiency Inertial CO_2 Extraction System (ICES)

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Presented at the

NETL CO_2 Capture Technology Meeting
Pittsburgh, PA
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Advanced Research Projects Agency • ENERGY

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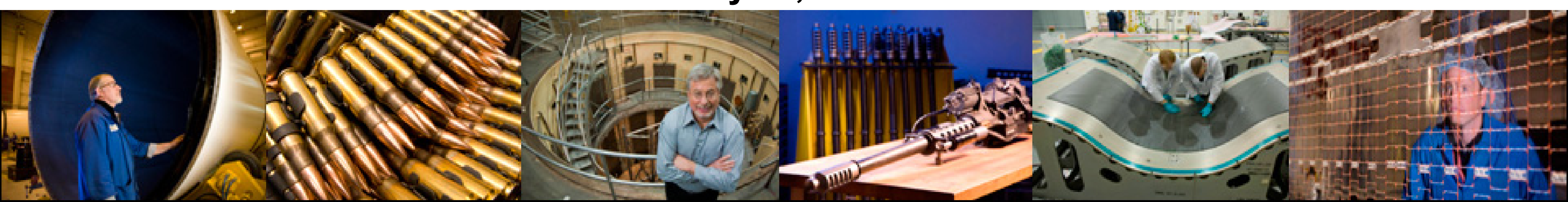
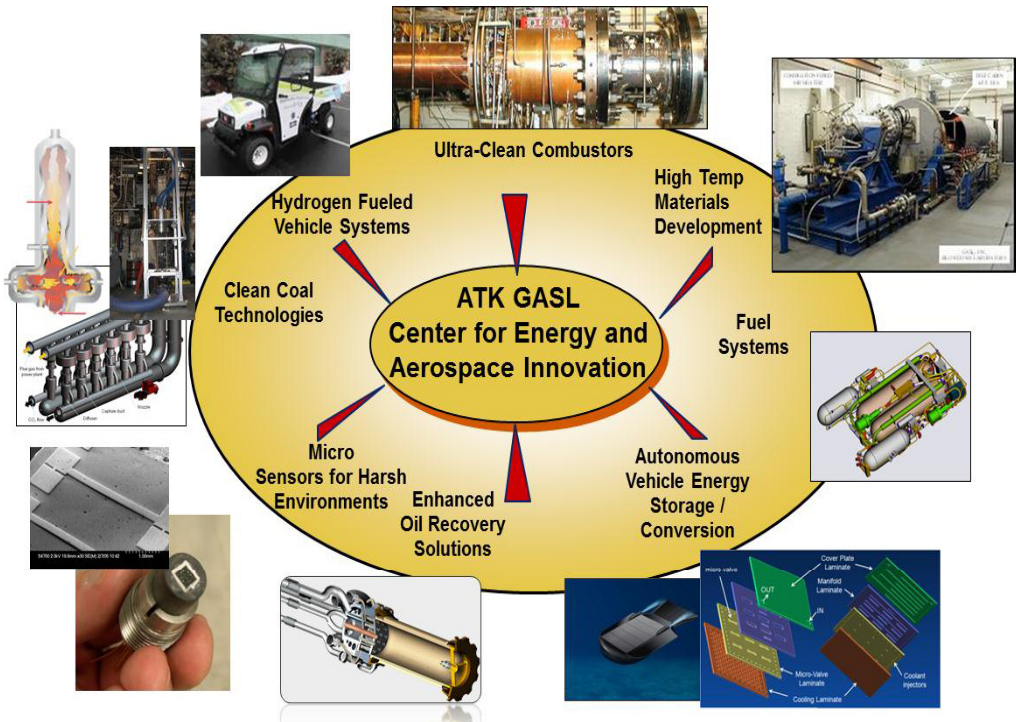


Company Backgrounds

- 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

Project Overview

Funding Summary:

ARPA-e:	$ 2,693 K
ATK and ACENT Cost Share:	$ 632 K
NYSERDA (New York State)	$ 200 K
TOTAL	**$ 3,525 K**

Project Performance Dates:

Phase 1:	July 2010 – March 2011 (completed)
Phase 2:	July 2011 – June 2013 (ongoing)

Project Participants:

Alliant Techsystems (ATK)

ACENT Laboratories LLC

WorleyParsons

Overall Project Objectives

- **Demonstrate proof-of-concept of aero-thermodynamic CO_2 condensation and separation**
- **Develop and benchmark analysis tools with experimental data to enable:**
  - Scaling of demo system to power plant size
  - Projection of economics in terms of COE and parasitic loads
- **Provide basis for next-phase slip-stream testing with real flue gas**
  - Minimize flue gas pressurization requirements
  - Maximize CO_2 capture (>90% goal)

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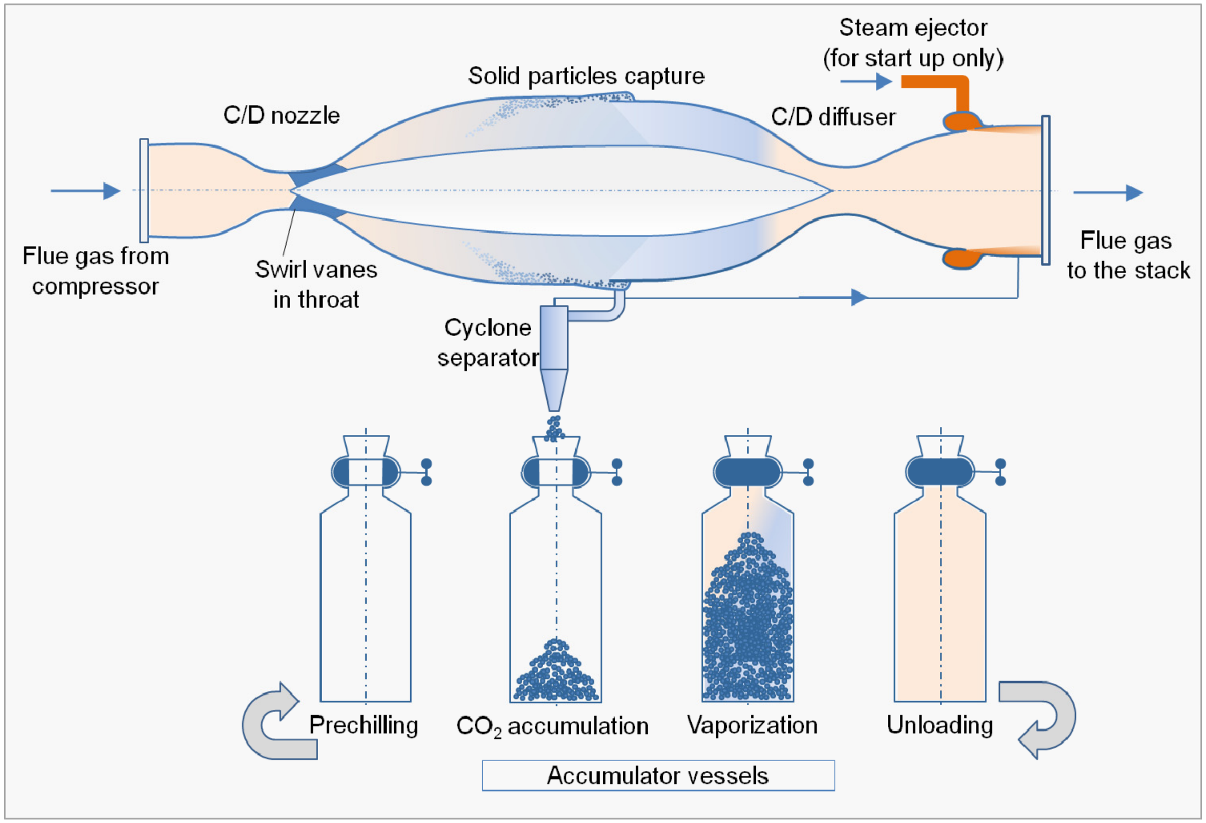
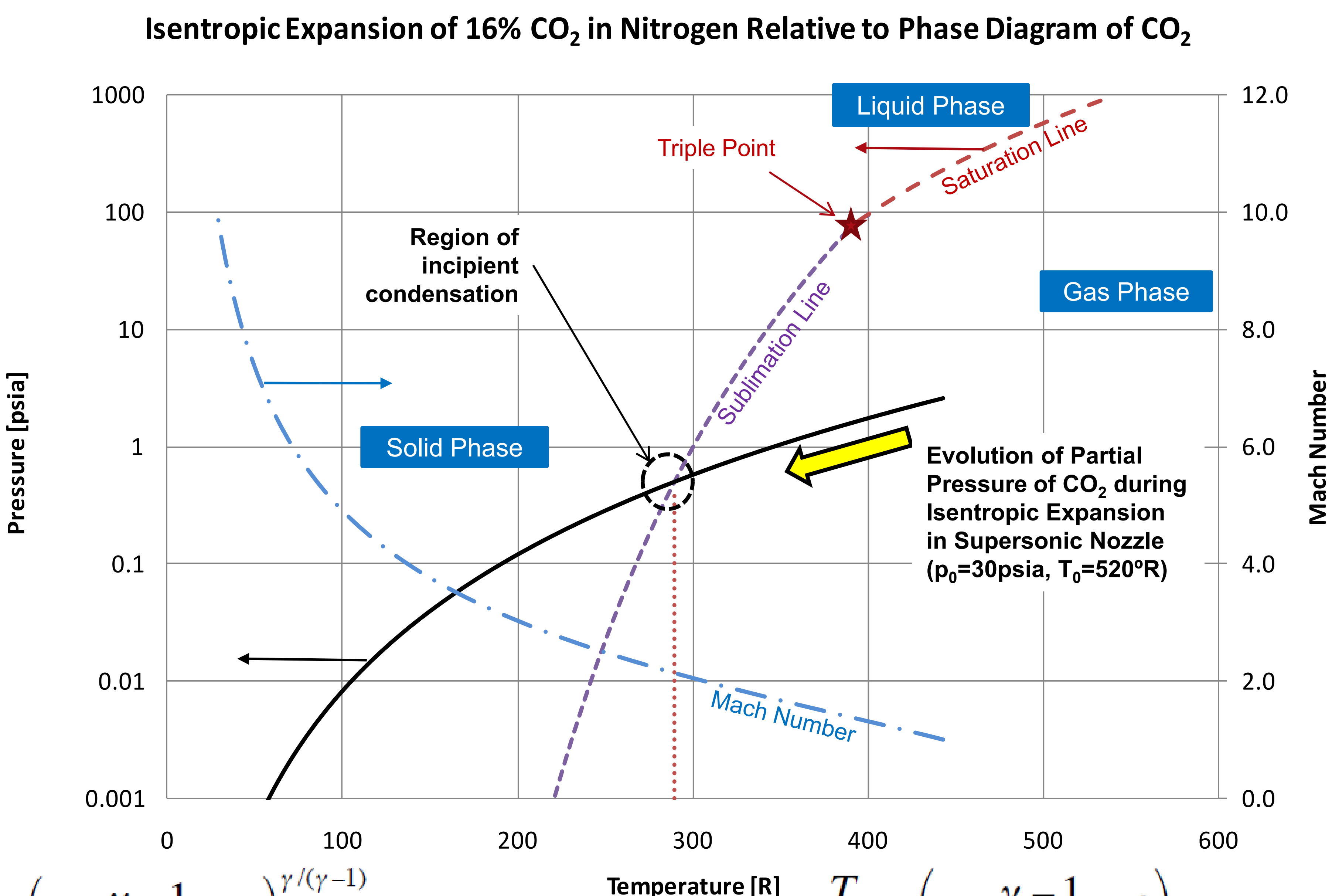
ICES Technology Fundamentals

- Pulverized coal power plant flue gas contains ~16% CO_2 in gaseous form at low pressure
- In ICES we compress flue gas to a moderate level and use the low temperature created by supersonic expansion to freeze the CO_2 in the flow
- ICES uses turning induced in the flow to inertially separate the solid particles from the gas stream



- We capture and collect the CO_2 (as dry ice) and then process using a self-pressurization system exploiting power plant waste heat

ICES on a P-T Diagram – Supersonic Expansion



$$\frac{p_0}{p_1} = \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\gamma/(\gamma-1)}$$

$$\frac{T_0}{T_1} = \left(1 + \frac{\gamma - 1}{2} M_1^2\right)$$

ICES Integration in PC Plant

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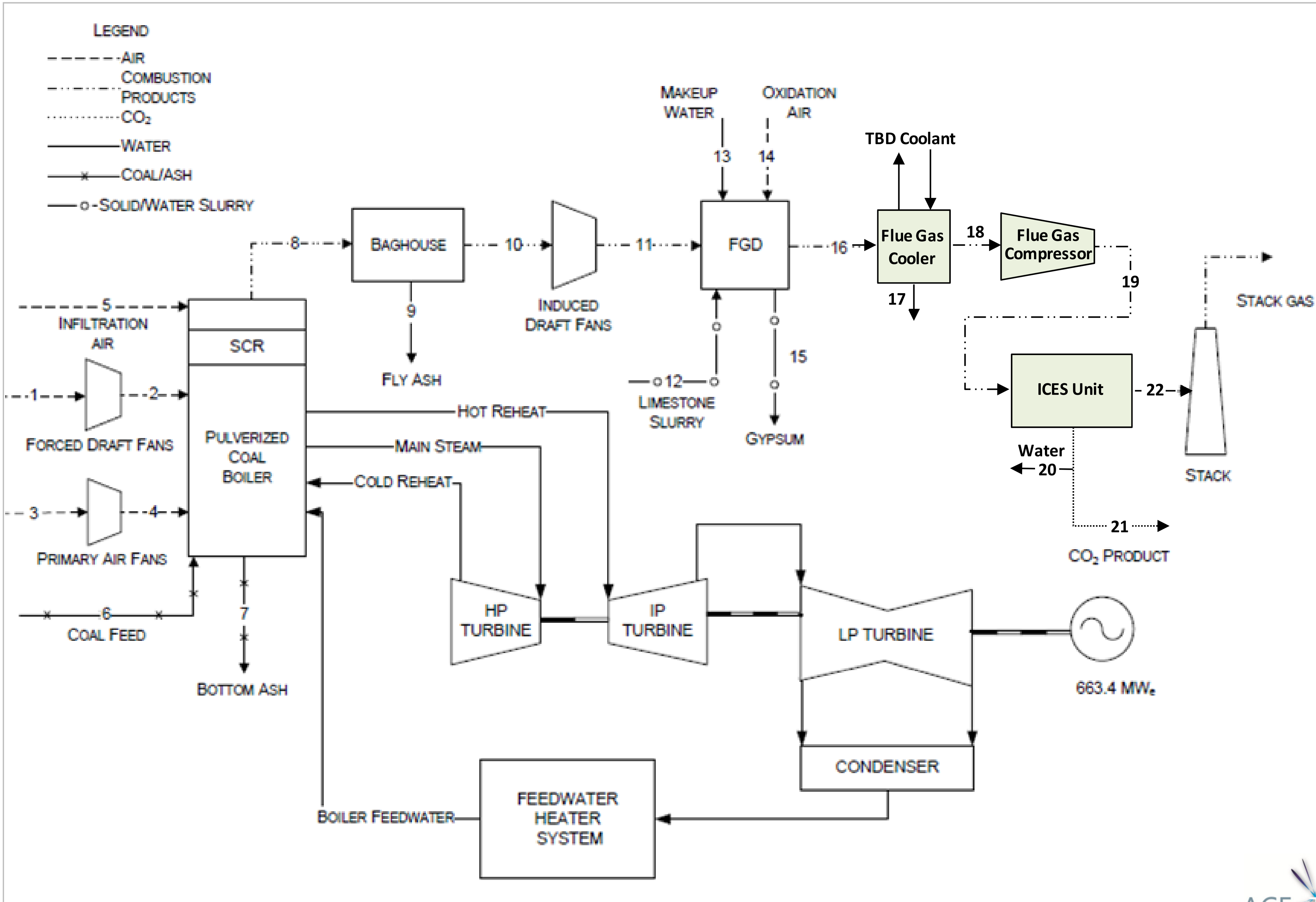

ICES System Schematic

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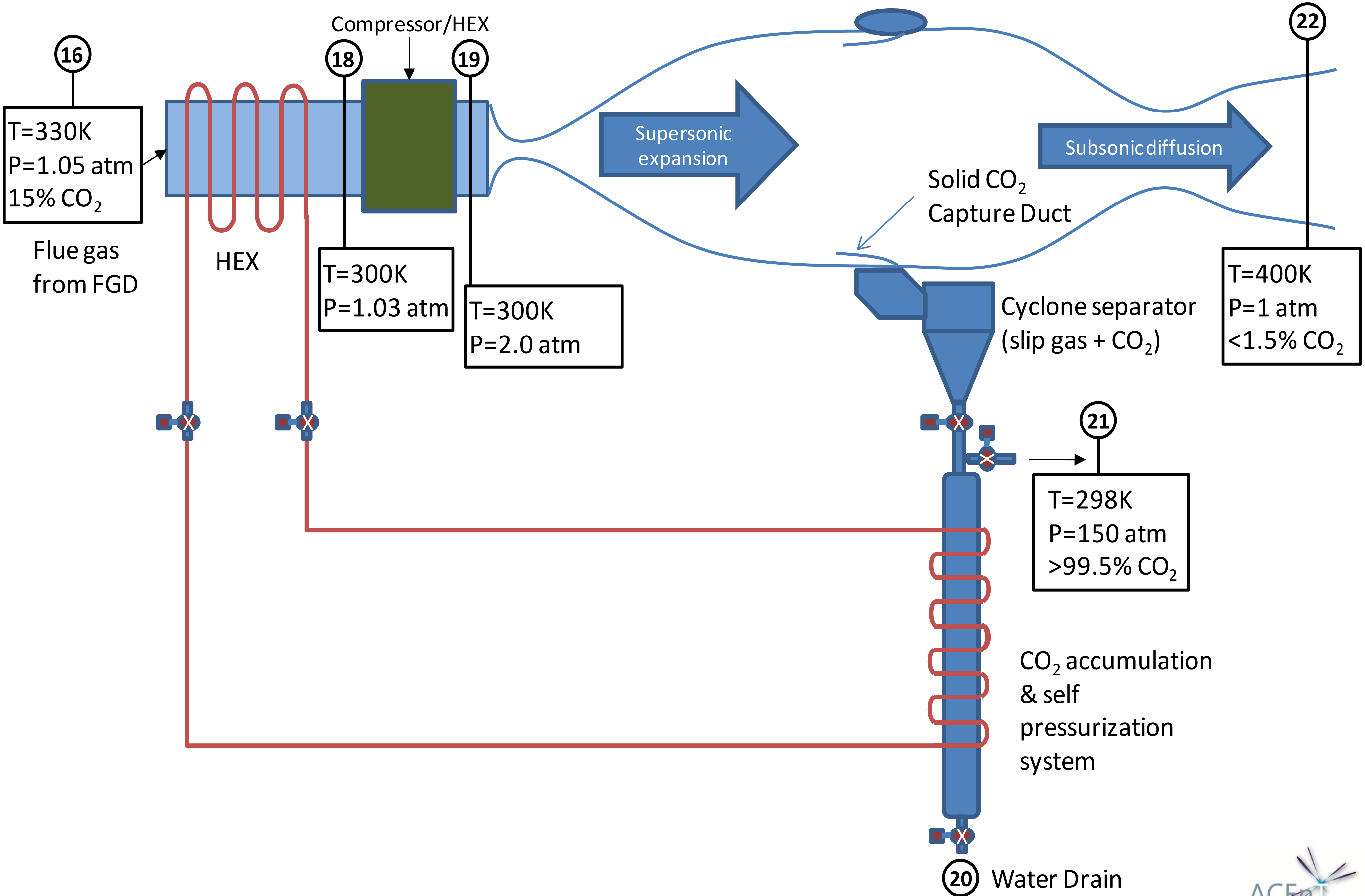
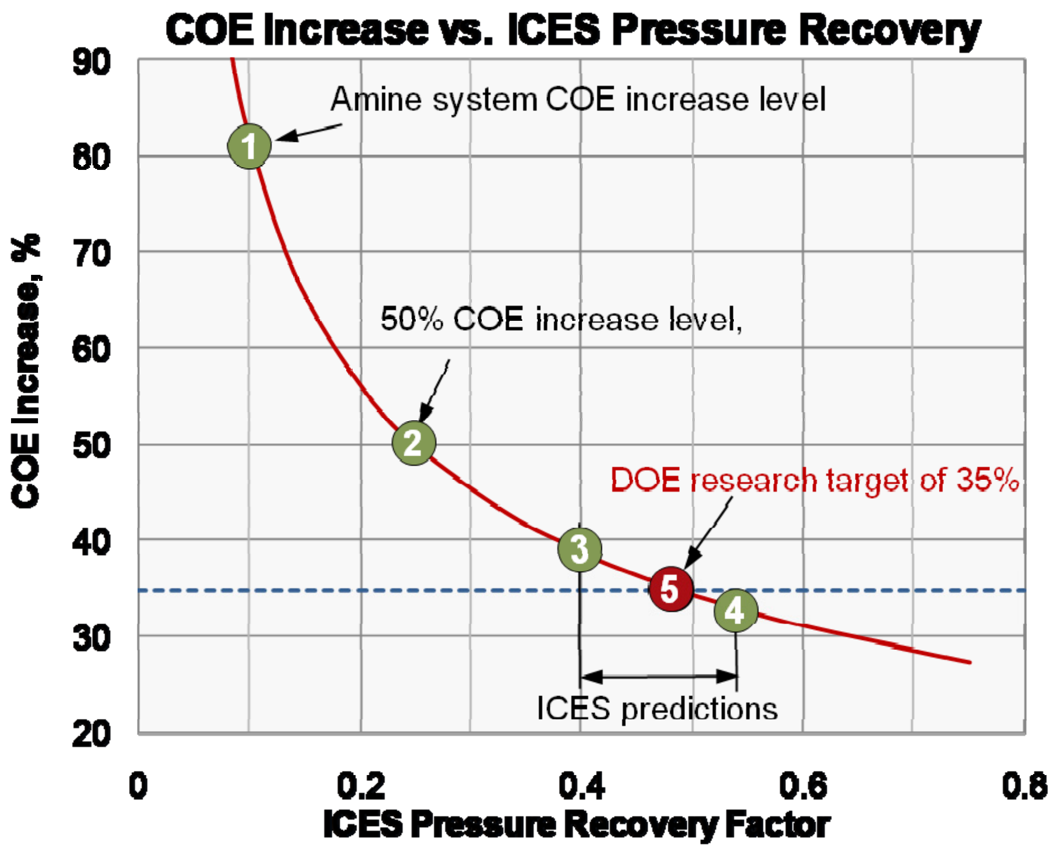


ICES Economic Impact

- ICES operating costs are driven by flue gas pre-compression
- Pressure recovery factor = P_{22}/P_{19}
- Low CapEx/OpEx combined with low power consumption result in a projected cost of electricity increase for CO_2 capture just over 1/3 that of the amine process
- Compression to 2,250 psi from low grade waste heat (constant volume heat addition to solid). Cost is limited to CAPEX + energy to move media.



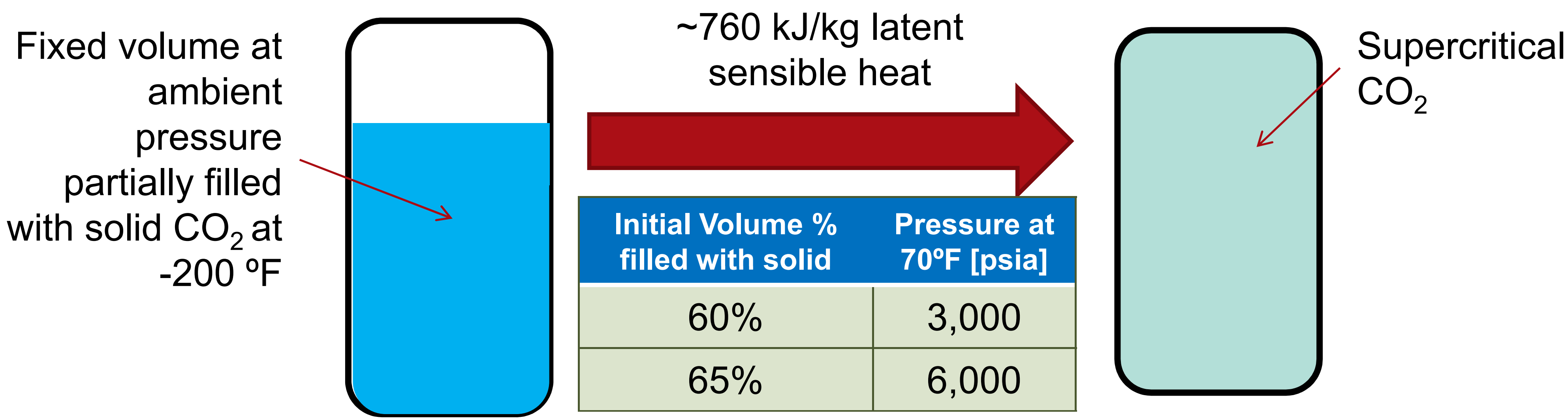
Metric	ICES	Amine
COE % increase	35%	81%
Parasitic Load	12.5%	21.5%
Cost per ton of CO_2 avoided	US$ 27	US$ 68

Energy Consumption

Process	Minimum Energy [kJ/kg CO_2]	ICES [kJ/kg CO_2]	Amine [kJ/kg CO_2]
Separation	-175	-683*	-
CO_2 Compression	-247	~68**	-
Total	-422	-751	-1,506

** Pre-compression of flue gas to 2 bar (absolute)*

*** + Approximately 760 kJ/kg of low grade waste heat used to compress CO_2 from solid phase to 2,250psia*



Initial Volume % filled with solid	Pressure at 70ºF [psia]
60%	3,000
65%	6,000

Compression energy is nearly "economically free" but it is not "thermodynamically free" i.e. this energy would otherwise be wasted

ICES Plant Integration and Footprint

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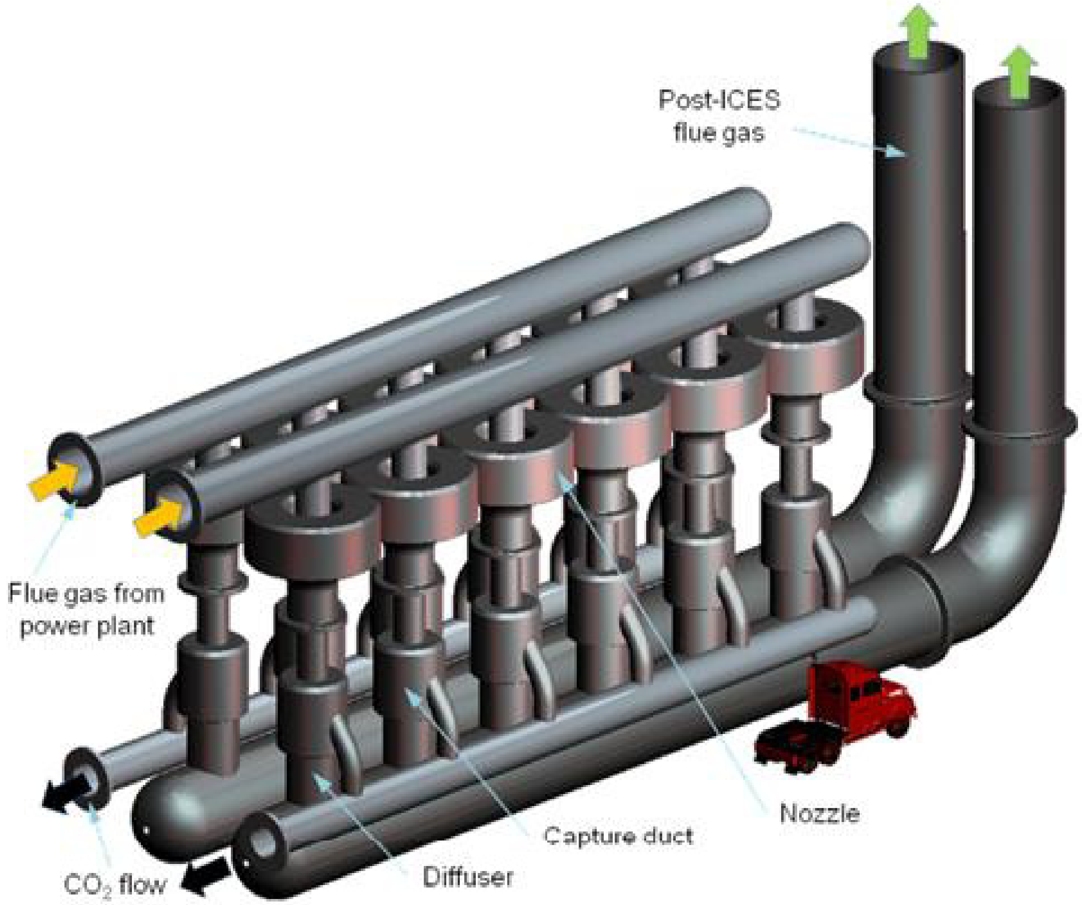
An ICES system sized for 545MW-equivalent flue gas contains twelve 60" ICES units (flue gas compression not shown)



L= 183 ft
W= 60 ft
H = 70ft

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

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 0.3-0.6 MW slip stream
  - The latest unit (0.3 MW) is 24” 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

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- 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

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Project Status – Phase 1

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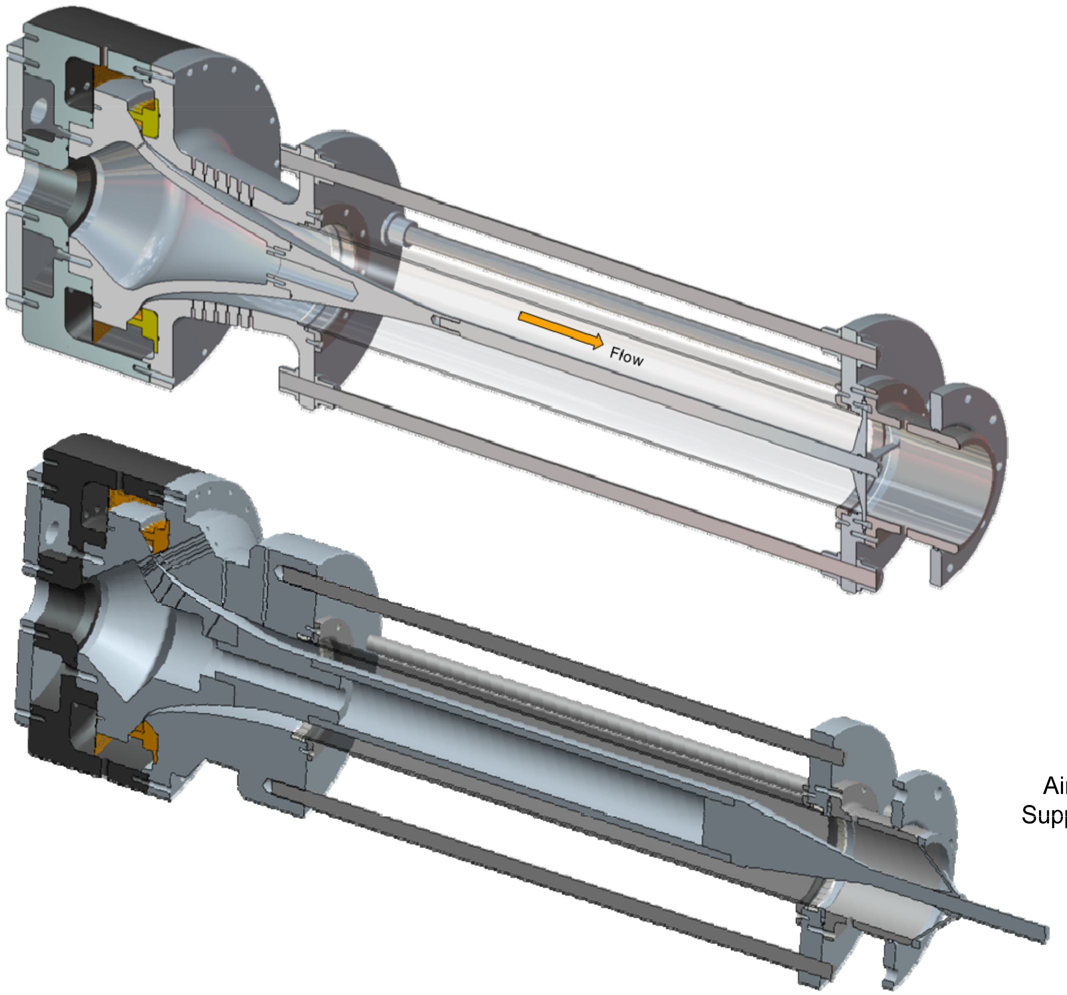
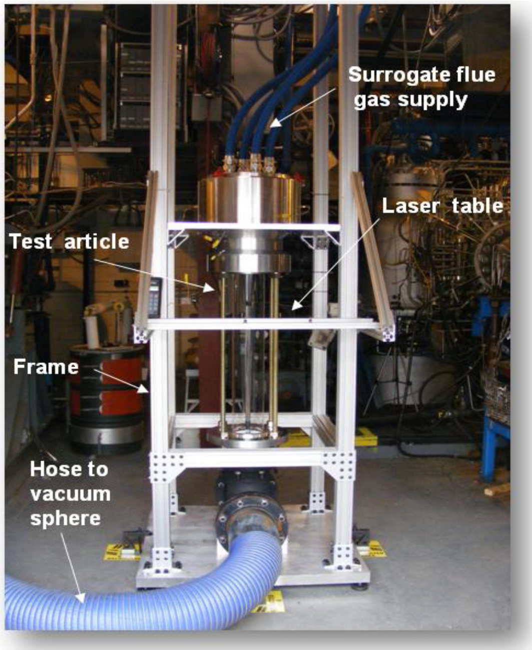
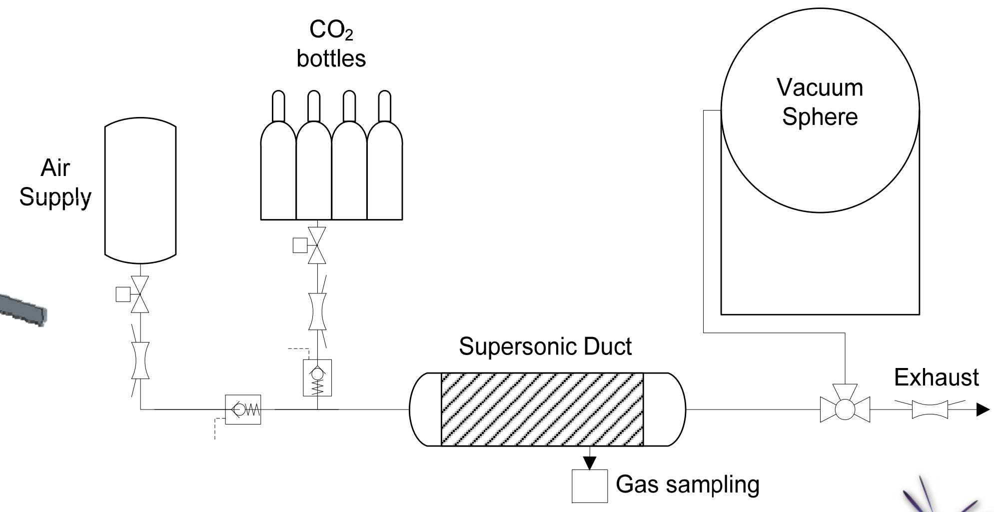
- **Phase 1 and early Phase 2 efforts focused on an axisymmetric system with swirl**



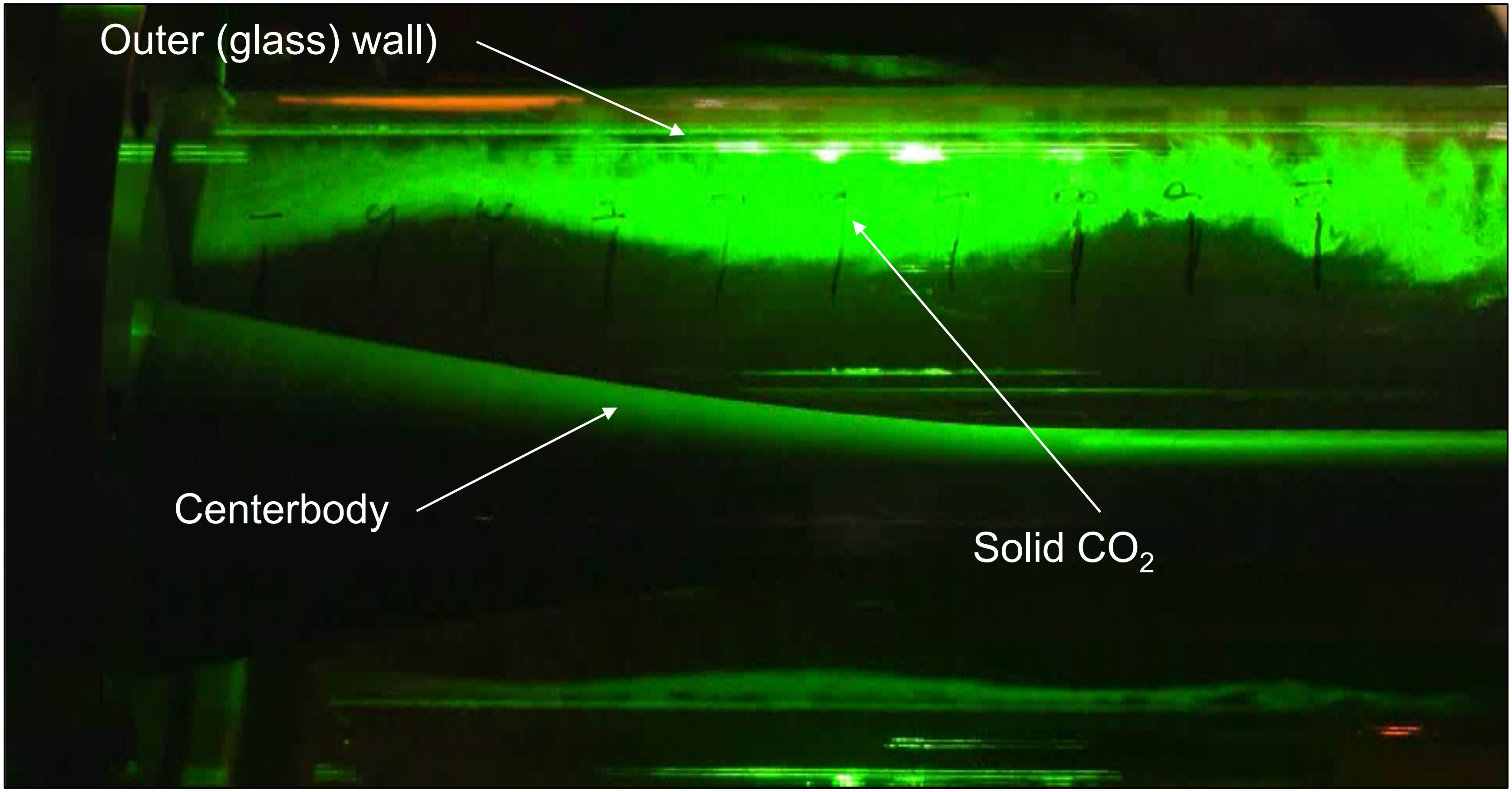


ICES test bench



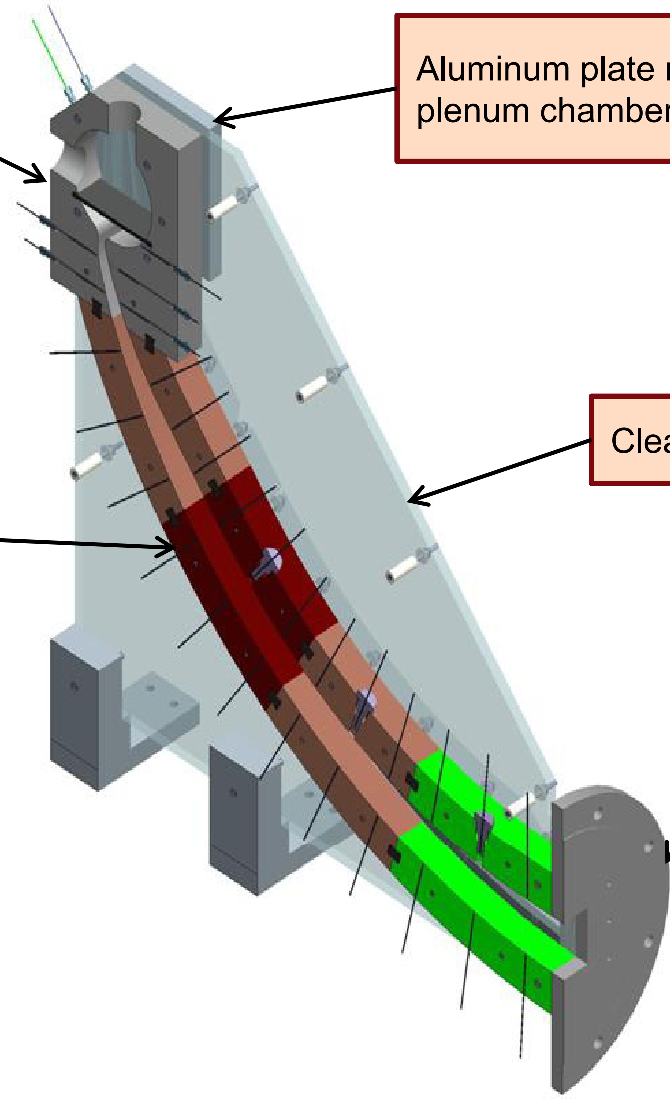
Axisymmetric System Results

Phase 1 data showed good CO_2 condensation and apparent, but erratic migration due to unsteady and separated flow



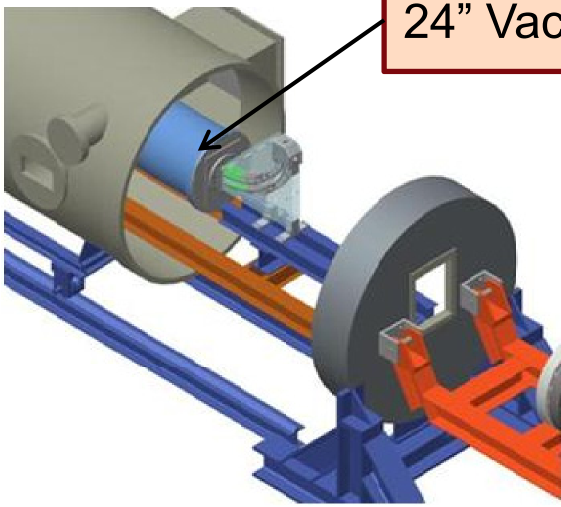
We recently changed to a 2D version of ICES

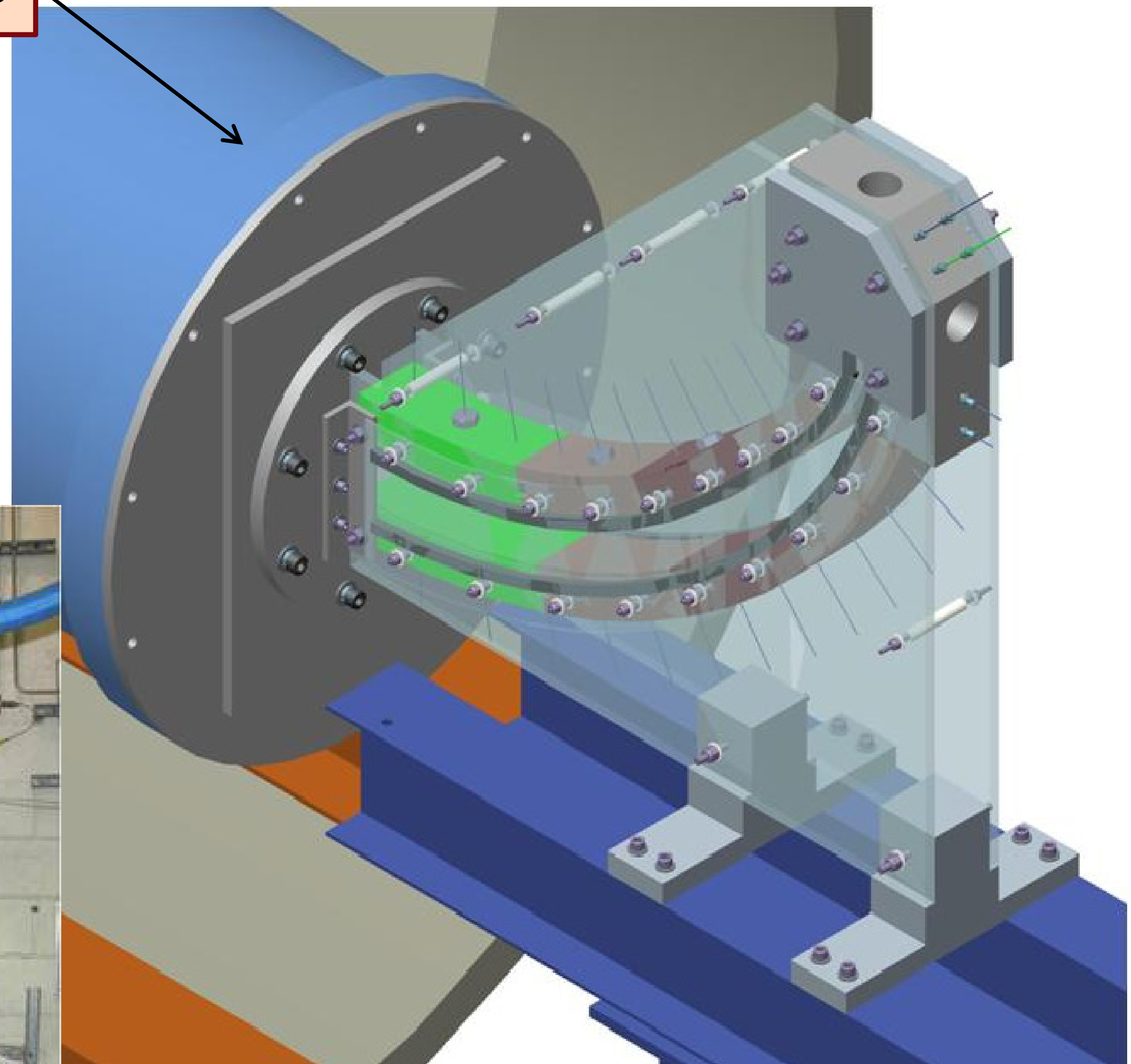
- Better aerodynamic performance (lower losses)
- Easier to fabricate and test
- No swirl vanes to induce turbulence/wake effects
- Simpler capture duct without swirl



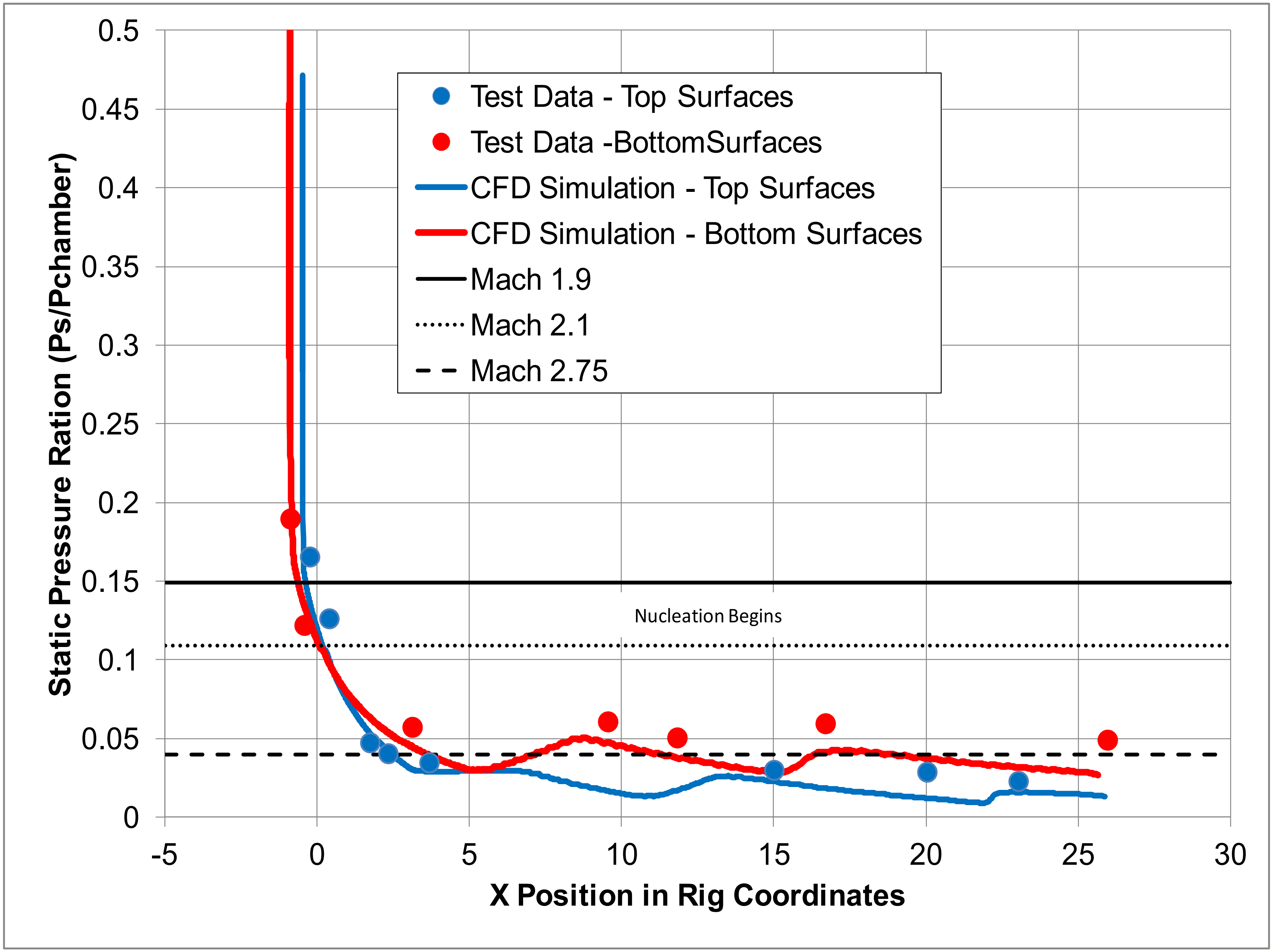
Gen5 Test Article Design – ATK Installation

24” Vacuum Pipe





Test Data Comparison to CFD – Static Pressure



Laser Particle Imaging Diagnostic

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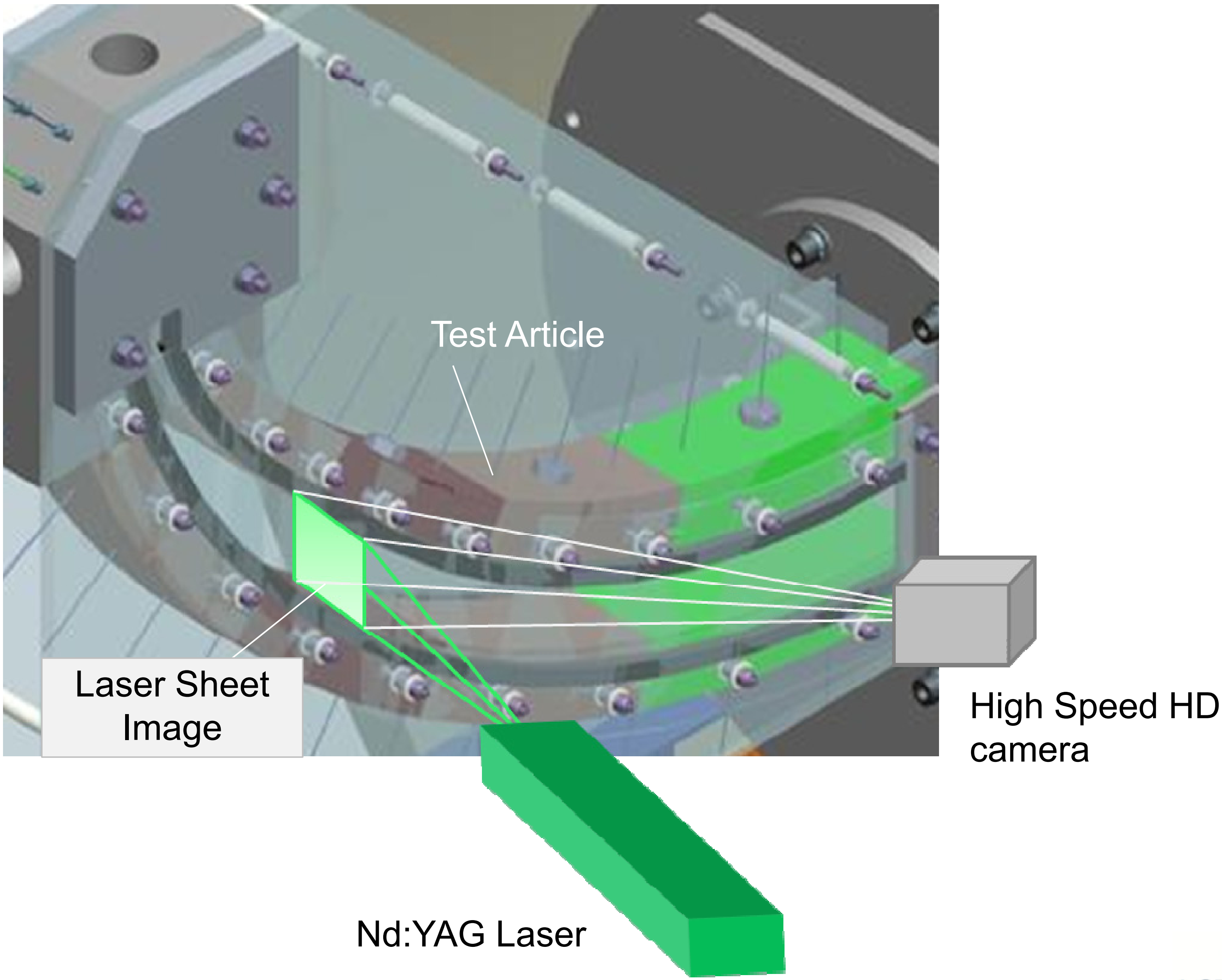

1, 10, and 100 Micron Particle Trajectories

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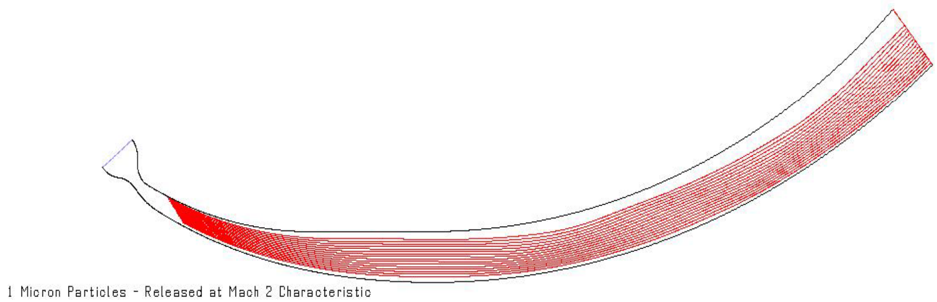
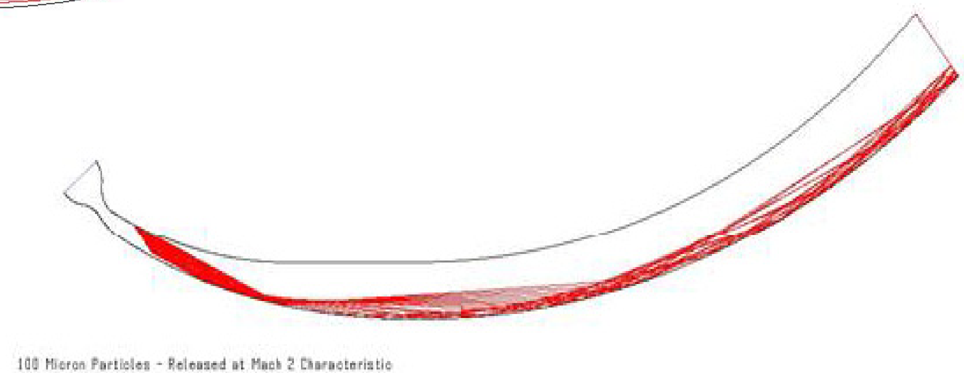
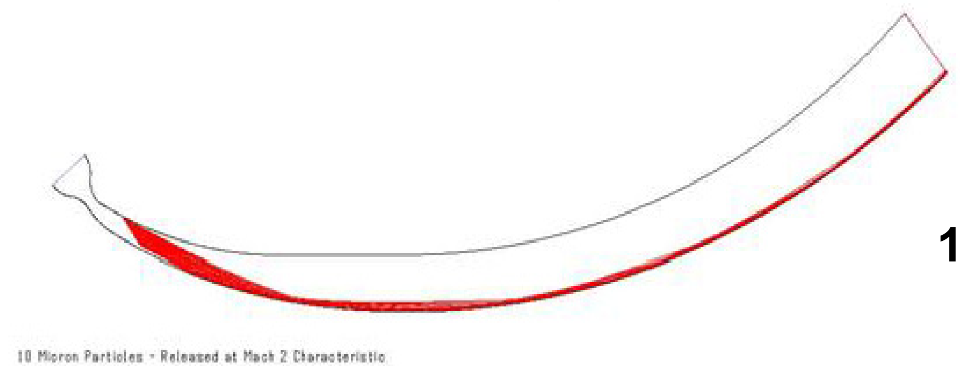


1 µm



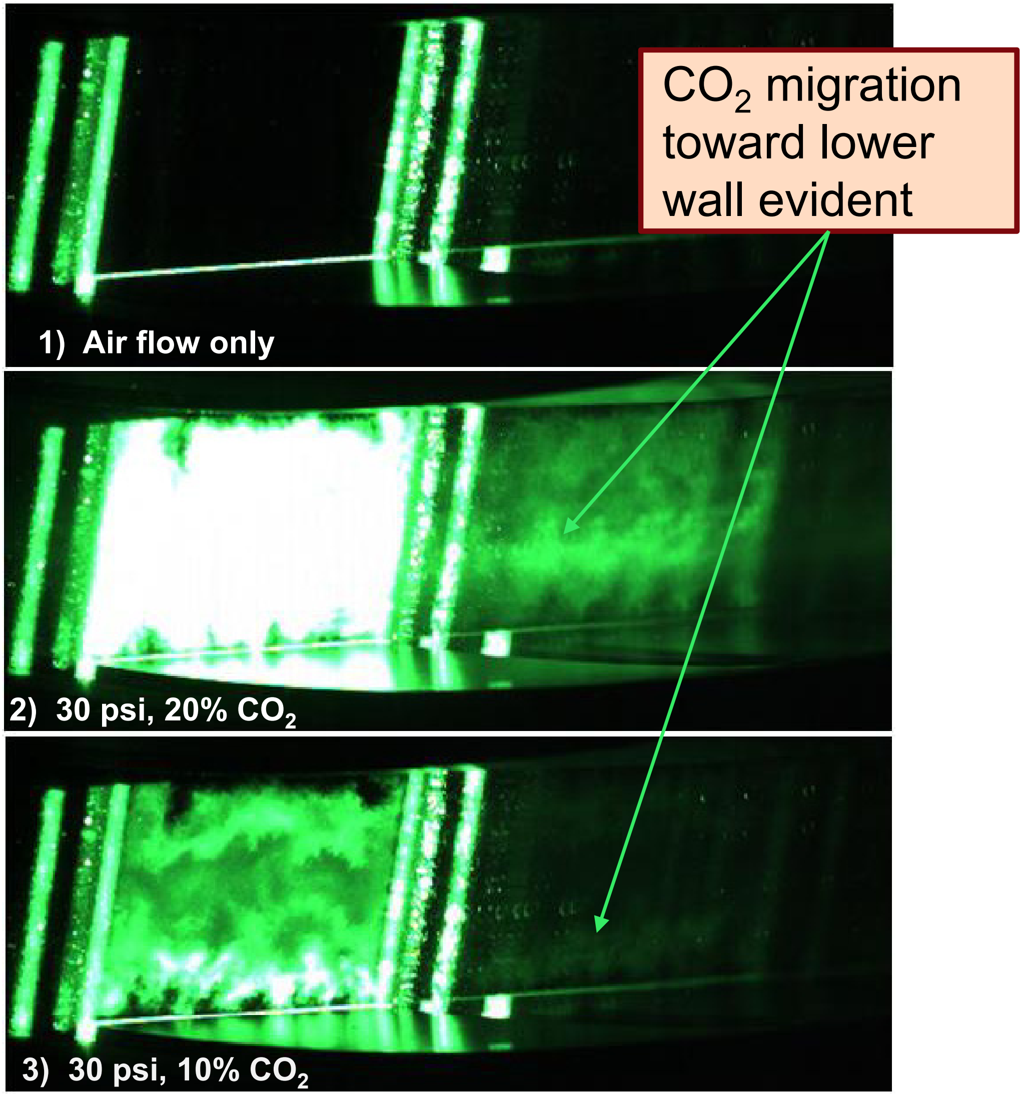
10 µm

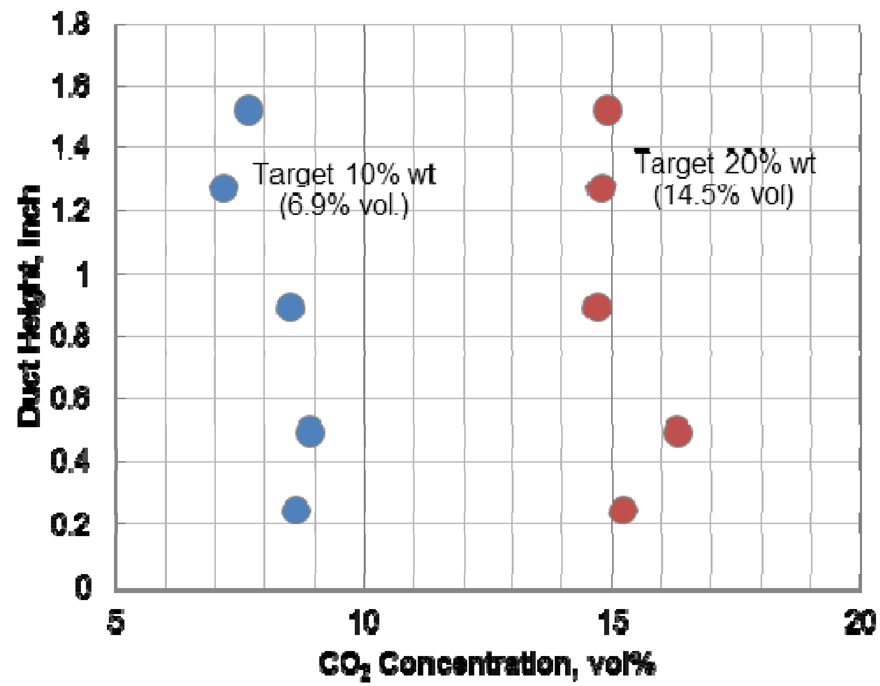


100 µm

At 10 microns+ particles separate and coalesce allowing for a slender capture slot

Three modes in typical ICES test





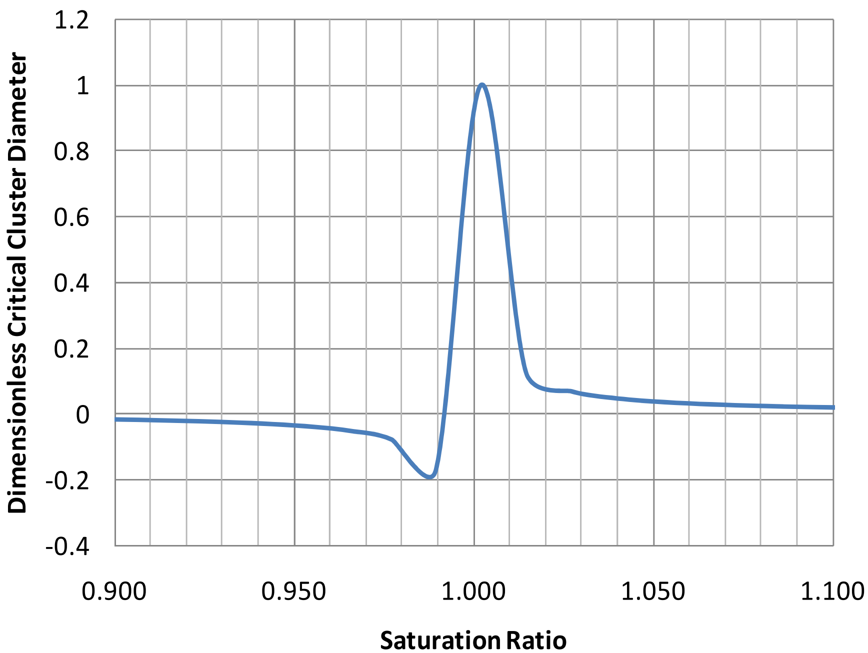
Optical and CO_2 sampling results show condensation as expected, but less than desired migration evident. Particle size does not appear large enough in these tests

Condensate Particle Size Control

- **Classical nucleation theory provides basis for predicting critical condensate cluster size and subsequent growth rate:**

$$r^* = \frac{2\sigma}{\rho_c RT \ln\left(\frac{p_v}{p_s}\right)} \qquad \frac{dr}{dt} = \alpha\left[1 - \left(\frac{p_v}{p_s}\right)^{\left(\frac{r^*}{r}-1\right)}\right]\left(\frac{m_c}{\rho_c}\right)\left[\frac{p_v}{(2\pi \bar{m}_c kT)^{1/2}}\right]$$

- **Both are strong function of the saturation ratio (*S*) = partial pressure of vapor/saturation pressure (p_v/p_s)**



- **Maximum initial cluster size near S=1**
- **Desirable to grow these clusters versus nucleating new ones at higher S**
- **Nozzle contour shape needs to be optimized for this purpose**
- **Need to further increase residence time of flow in this critical region**
- **Increasing scale toward power plant size will help**

Current Plans

- **Remaining portion of Phase 2**
  - Investigate flow seeding with solid CO_2 (self generated) and other media to promote large particle formation (ongoing)
  - Update contour to further optimize particle size
  - Integration of capture duct to remove CO_2
  - Integration of diffuser to return flow to atmospheric pressure with minimal losses
- **“Phase 3”**
  - Ideal next step desired is a slip stream test, e.g. at the National Carbon Capture Center (NCCC)

Accomplishments to date

- Three ICES configurations have been developed and tested to date
- Demonstrated clean nozzle flow with low apparent losses (to be verified with later diffuser tests)
- Demonstrated supersonic condensation with some migration
- Plans in place to increase particle size to achieve desired migration performance

Acknowledgements

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BACKUP

Schematic of Condensation Process

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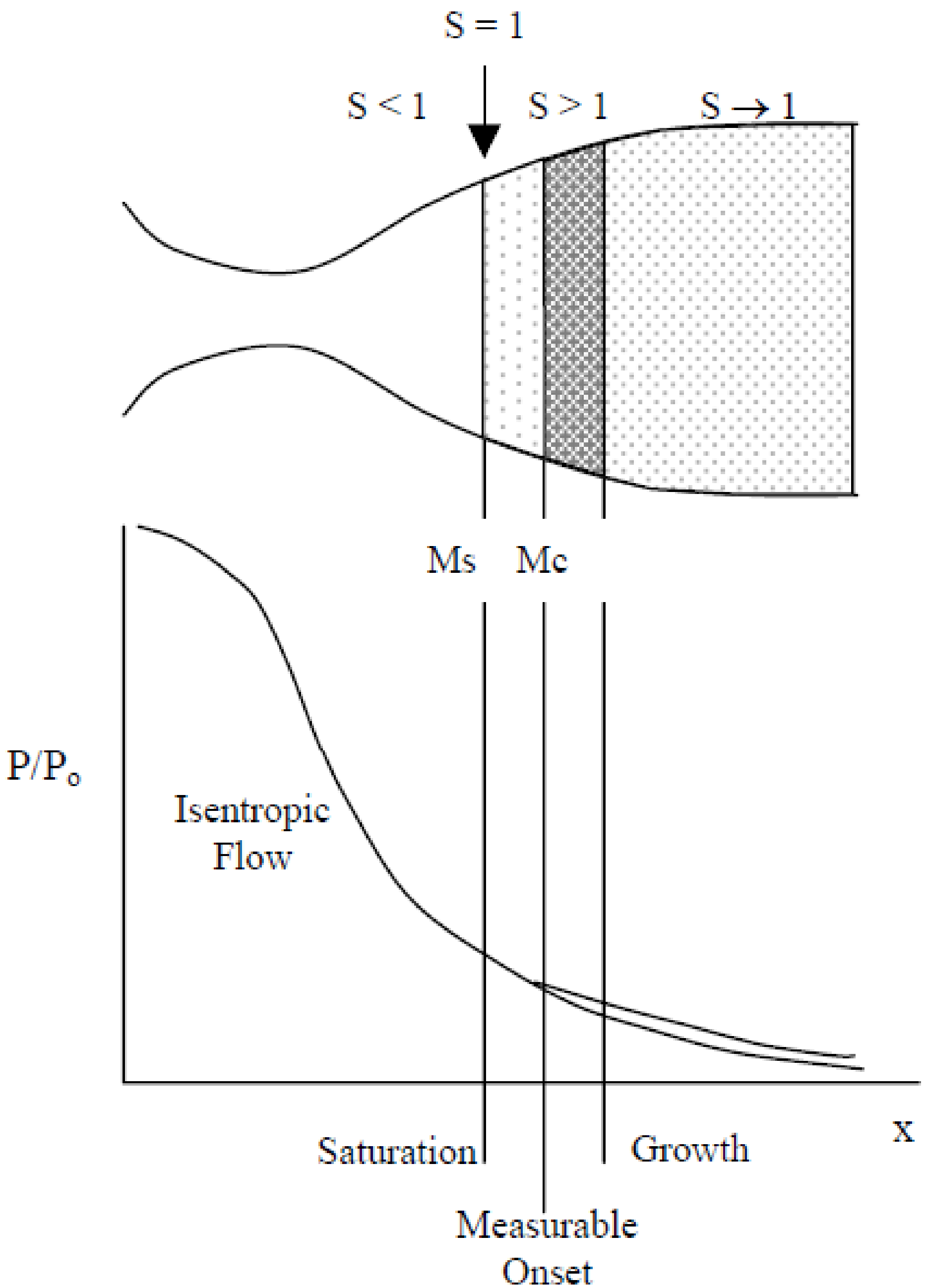

***S** = **p**$_s$ / **p**$_v$, where **p**$_v$ is the partial pressure of the vapor and **p**$_s$ is the* vapor saturation pressure at the temperature of the system.

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