Flow Modeling and Testing of ESPs

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Outline

- Introduction
- ESP Fluid Flow Basics
- Flow Modeling
  - Physical scale
  - CFD
- Questions

ESP Fluid Flow Basics

- Primary goal: Maximize particulate capture

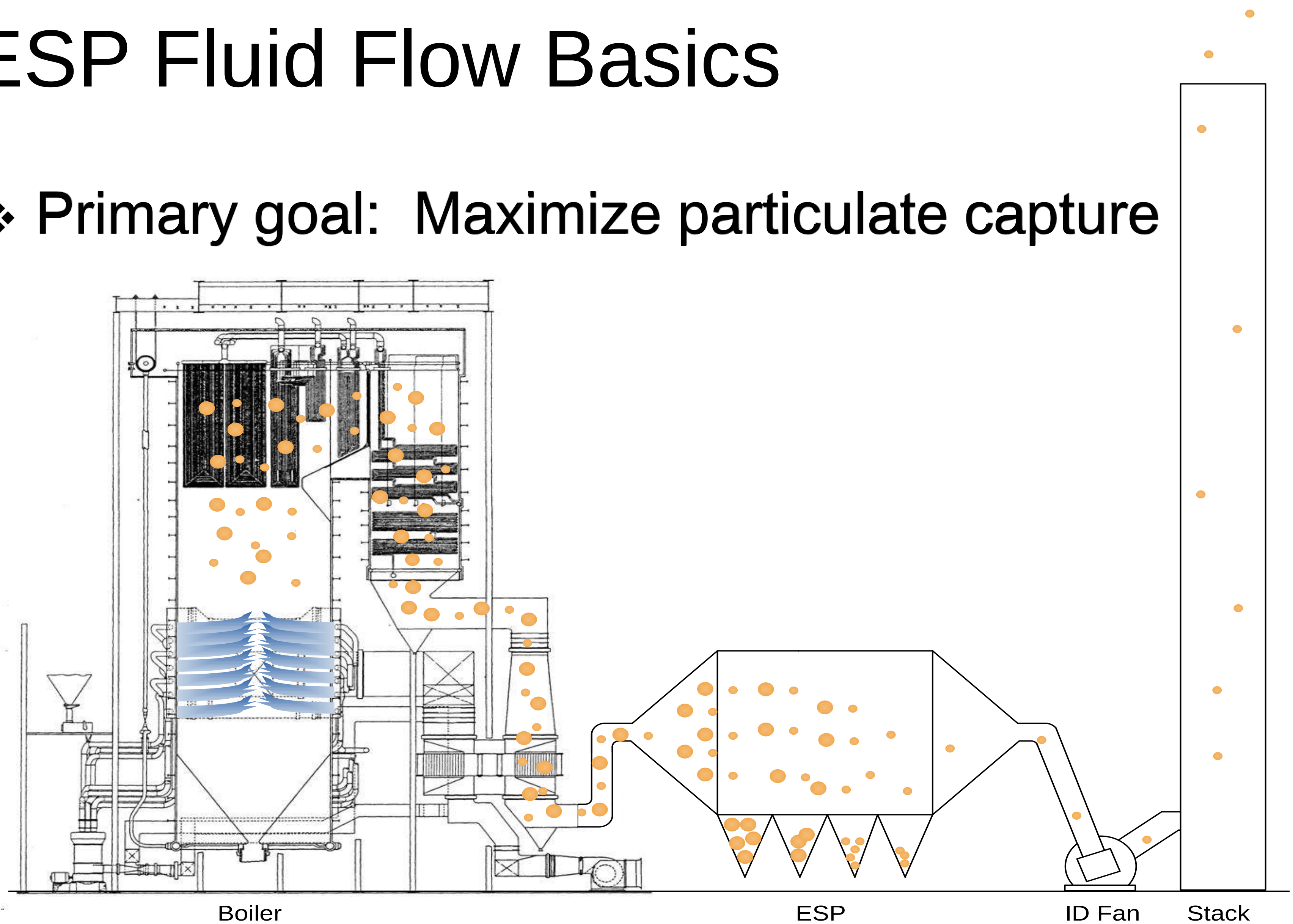


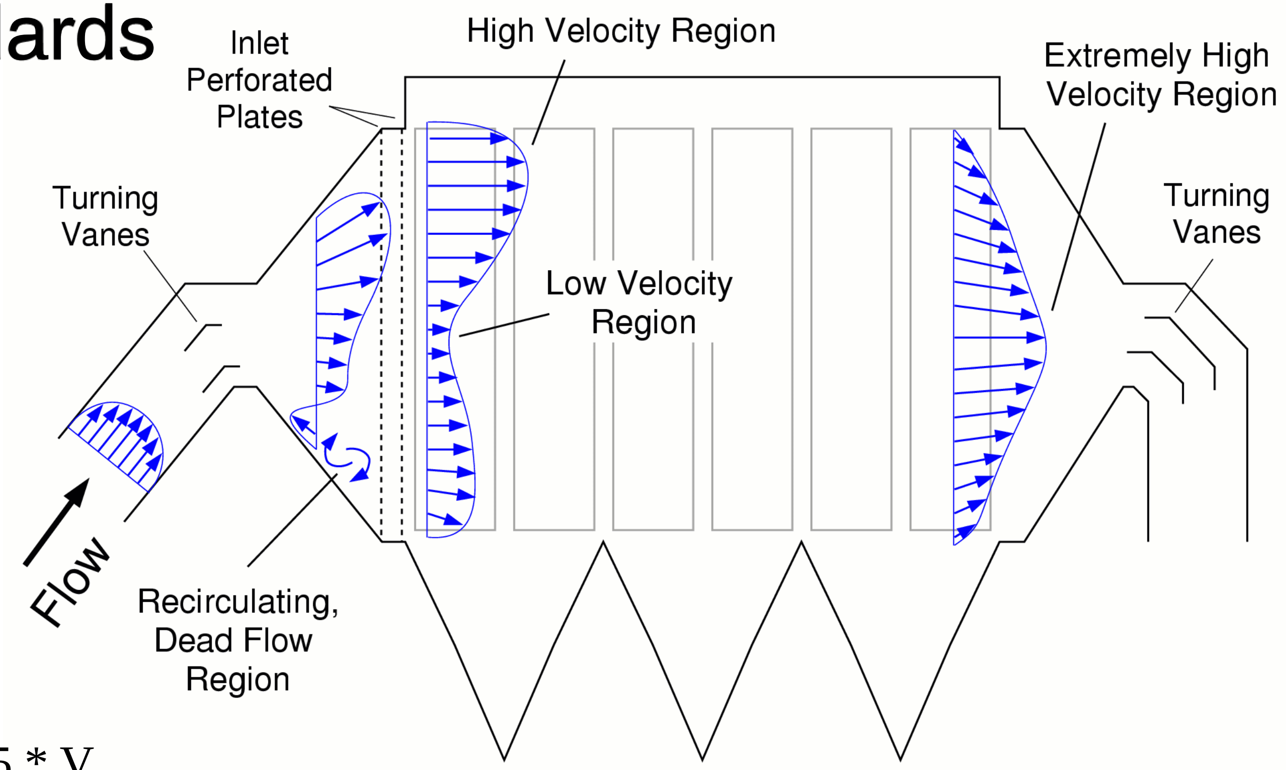
Image: Gerry Klemm, Southern Company

ESP Fluid Flow Basics

- Flow Related Goals
  - Uniform gas velocity through collection fields
  - Equal flow balance between multiple chambers
  - Avoid hopper re-entrainment
  - Avoid particulate deposition / drop out
  - Minimize peak velocities / erosion
  - Minimize pressure drop
  - Uniform temperature distribution
  - Sorbent injection / mixing

Gas Velocity Distribution

- ❖ Uniform velocity within collection region
- ❖ Industry standards
  - ICAC
  - RMS/CV deviation



ICAC: 85% of velocities $\leq 1.15 * V_{avg}$

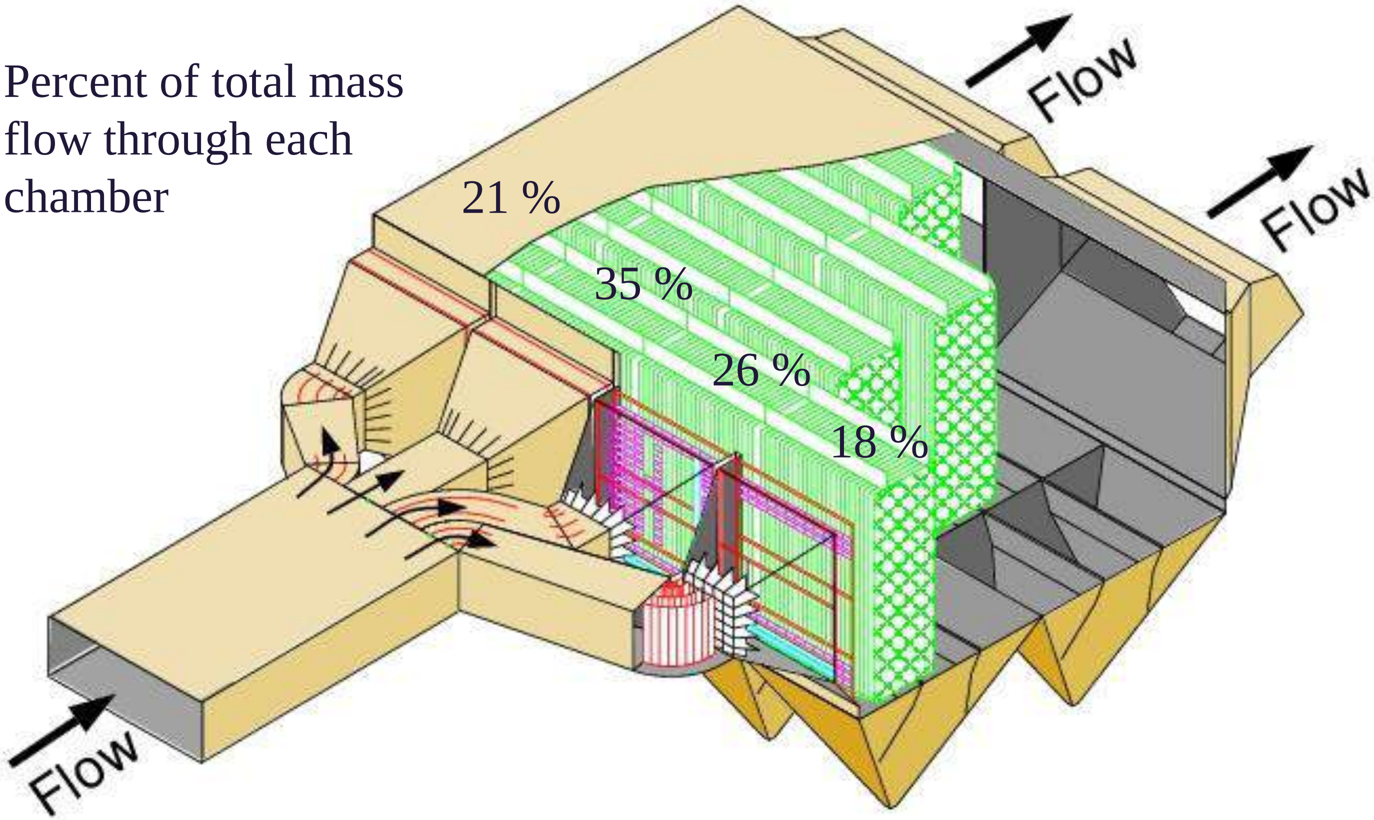
99% of velocities $\leq 1.40 * V_{avg}$

Other: % RMS Deviation $\leq$ 15% of V_{avg}

Gas Flow Balance

- ICAC goal: flow within ±10% per chamber

Percent of total mass flow through each chamber



ICAC: Flow within each chamber to be within ±10% of its theoretical share

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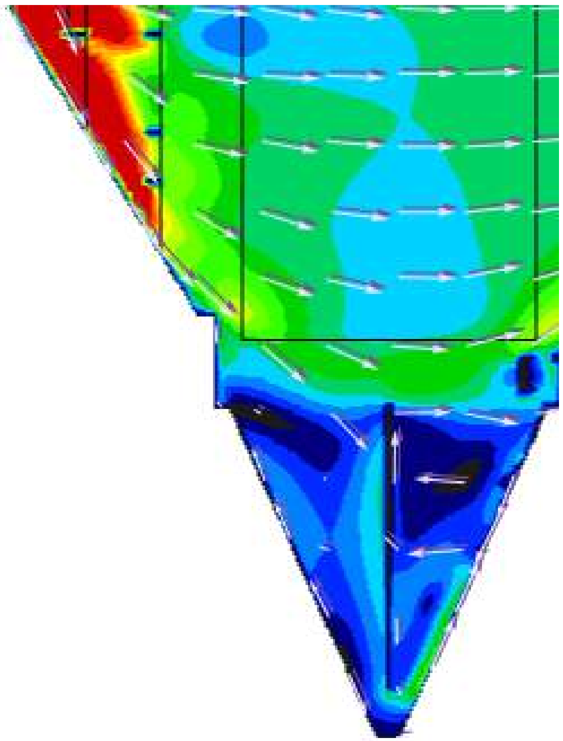
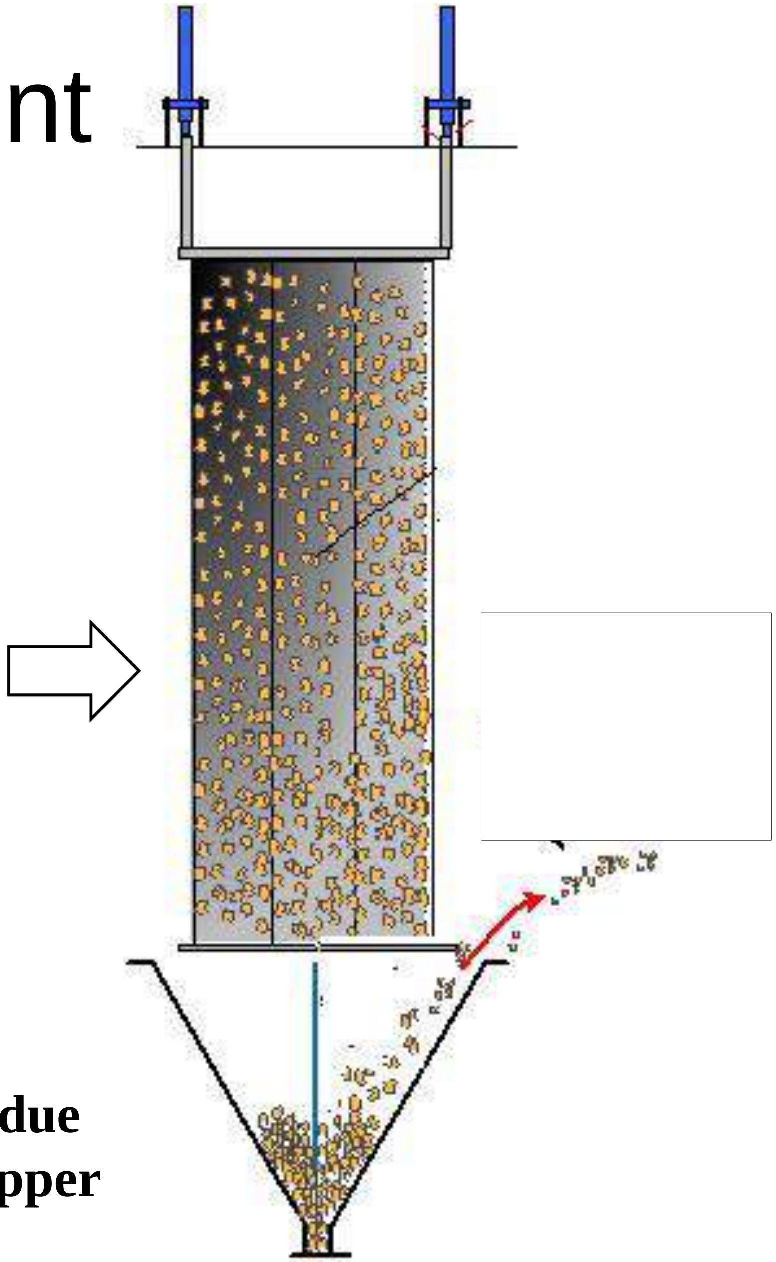
Hopper Re-entrainment

- Avoid gas flow in hoppers
- Avoid sweepage





Particles escape due to gas flow in hopper

Image: Gerry Klemm, Southern Company

Particulate Deposition

- Duct floors
- Turning vanes
- Perforated plates

Particulate Deposition

- Extreme deposition = structural failure

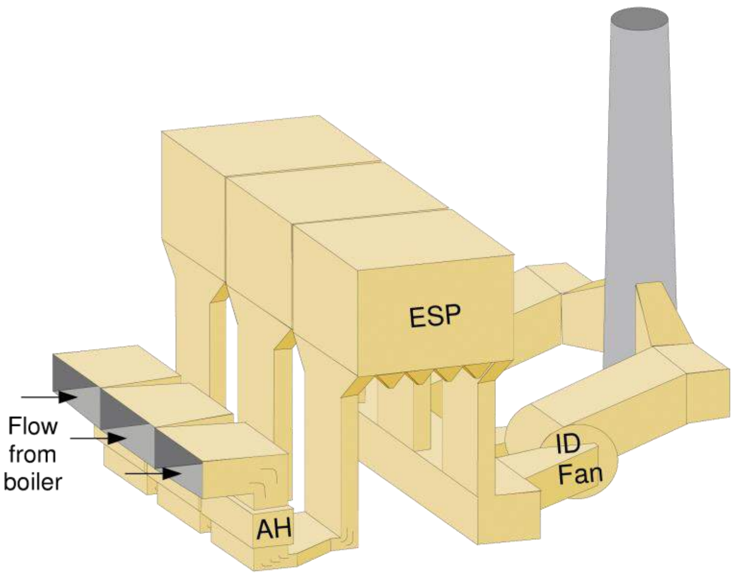
Peak Velocities / Erosion

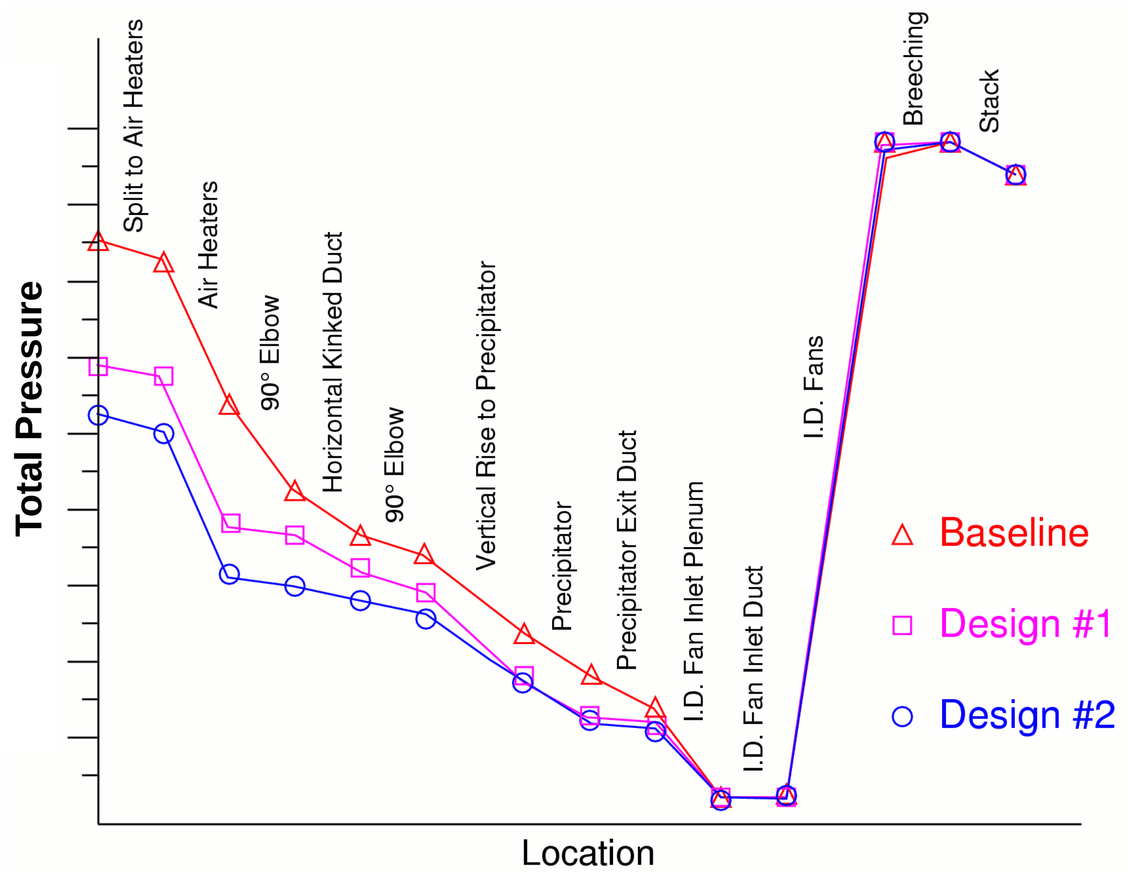
❖ Erosion potential depends on
- Impact velocity (to the 2.5 power)
- Flow rate
- Hardness, shape
- Angle of impact

❖ Erosion issues
- Vanes
- Baffles
- Perforated plates
- Ductwork
- Trusses

Pressure Drop

- General goal:
  - Minimize DP

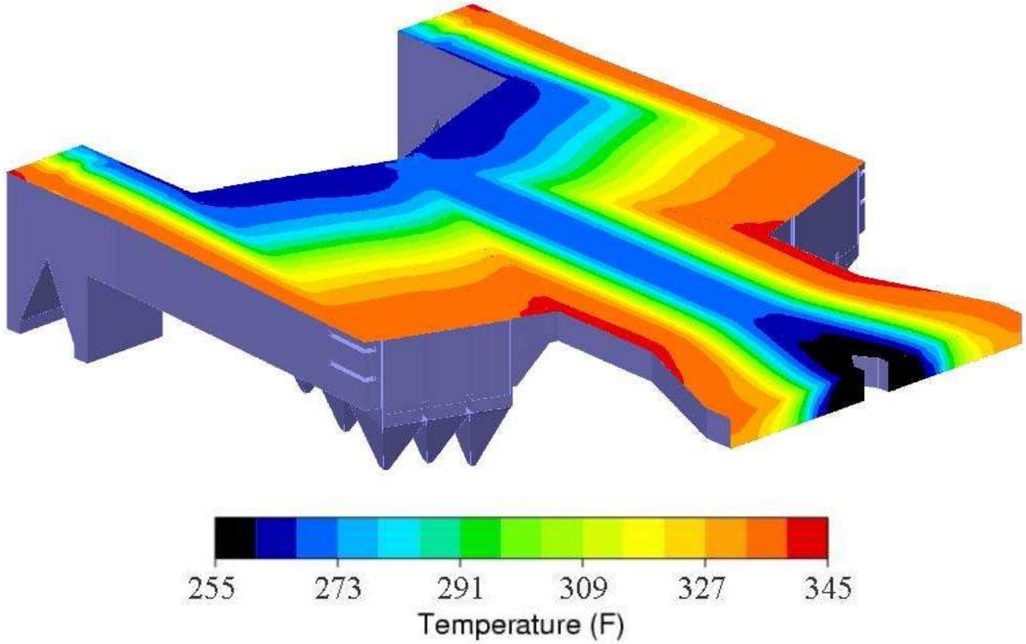


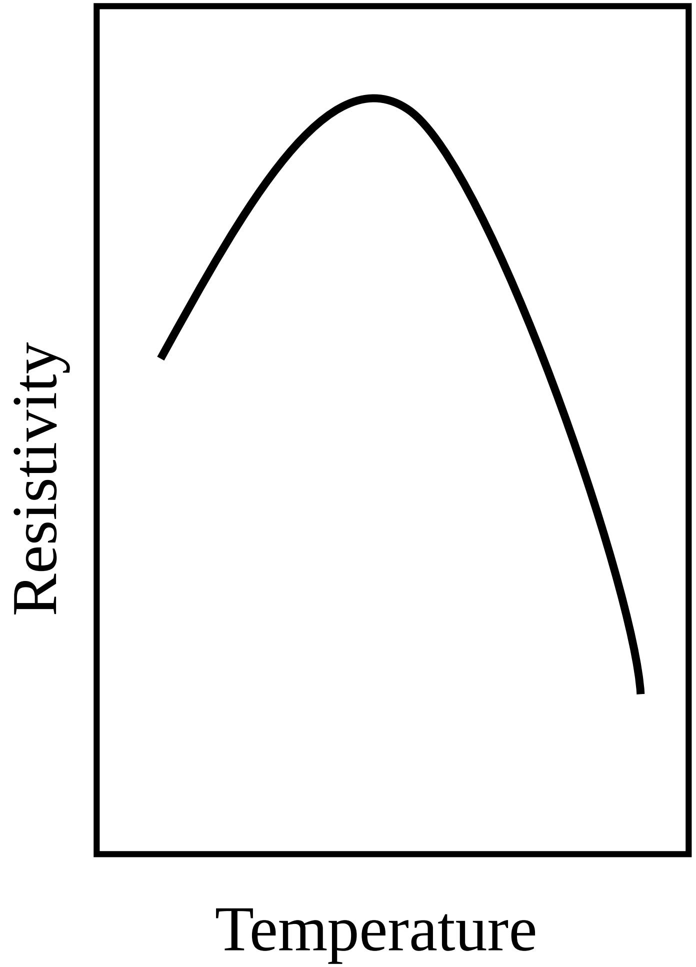


Ductwork redesign saves
2.1 IWC (520Pa)

Gas Temperature

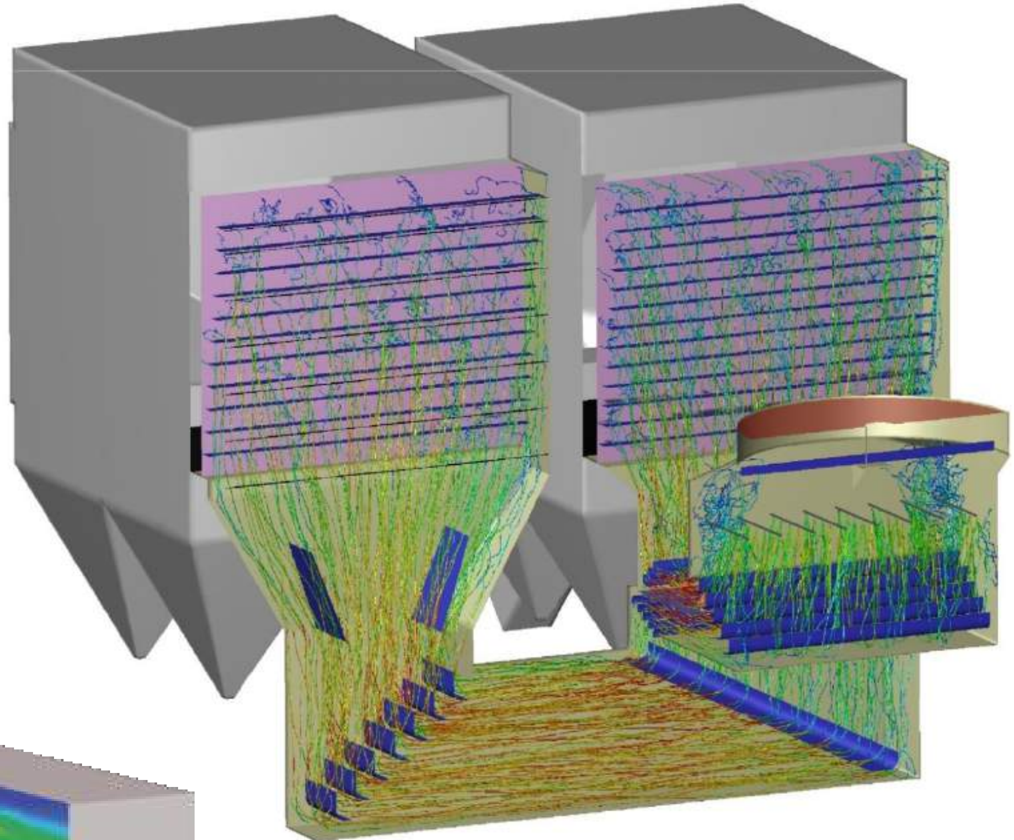
- Temperature stratification
  - Resistivity
  - Corrosion
  - Sorbent performance

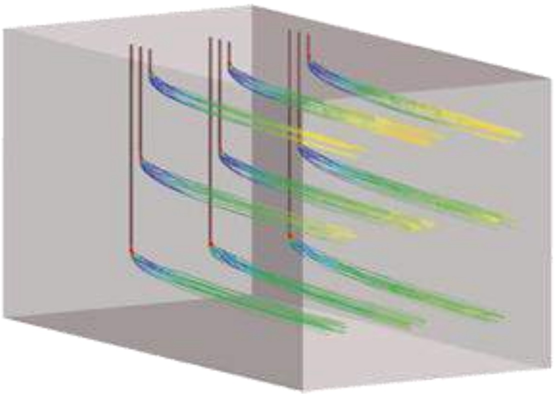


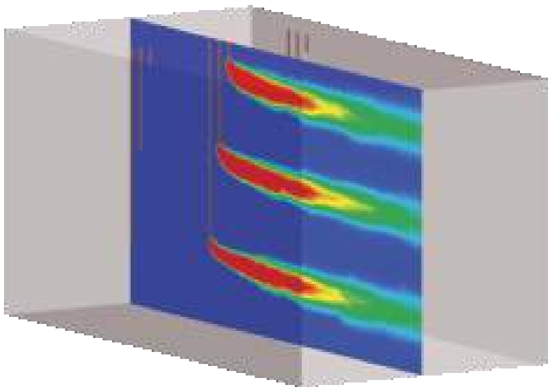


Injection Systems

- Gaseous injection
  - SO3, NH3, others
- Particulate injection
  - Activated carbon
  - Trona, SBS, lime, etc.







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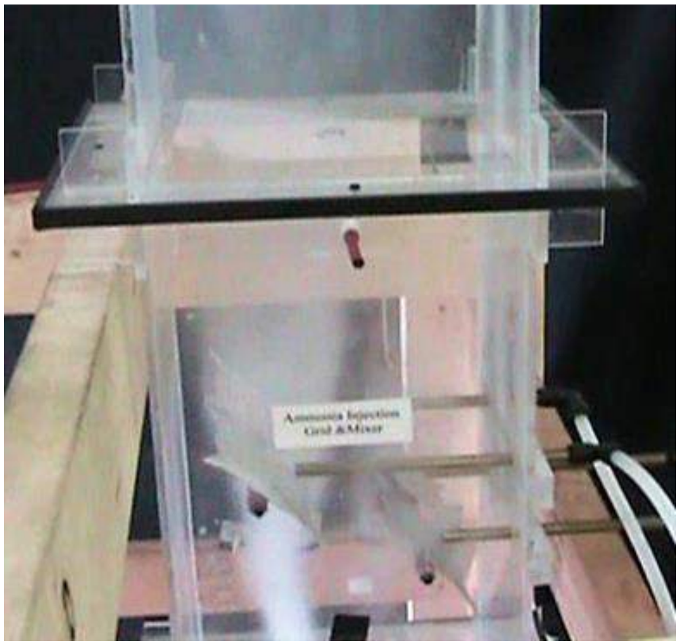
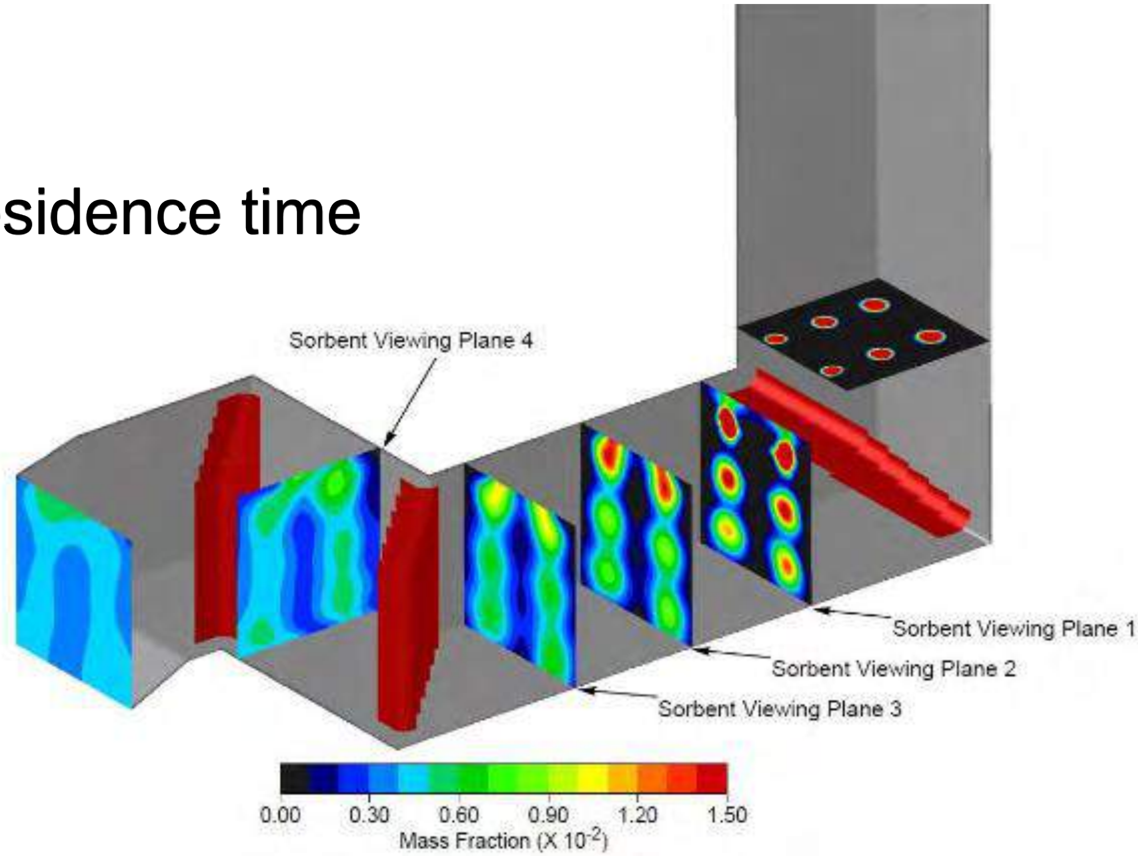
Sorbent Injection

- Goals
  - Uniform distribution
  - Surface contact / residence time
  - Mixing / dispersion





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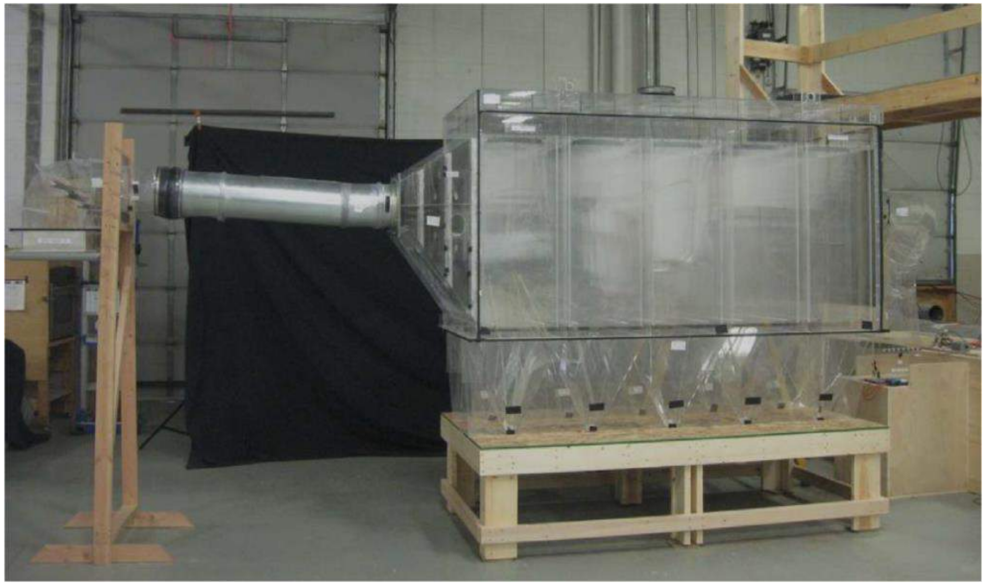
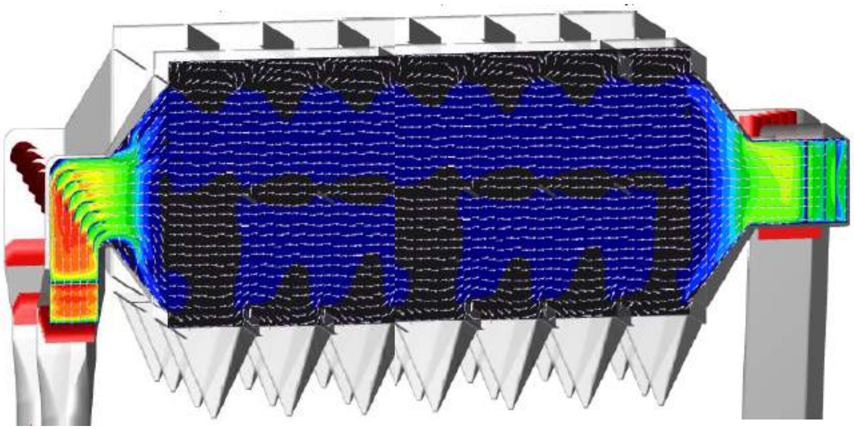
ESP Modeling

- ❖ Physical Model Testing
- ❖ Computational Fluid Dynamics (CFD)



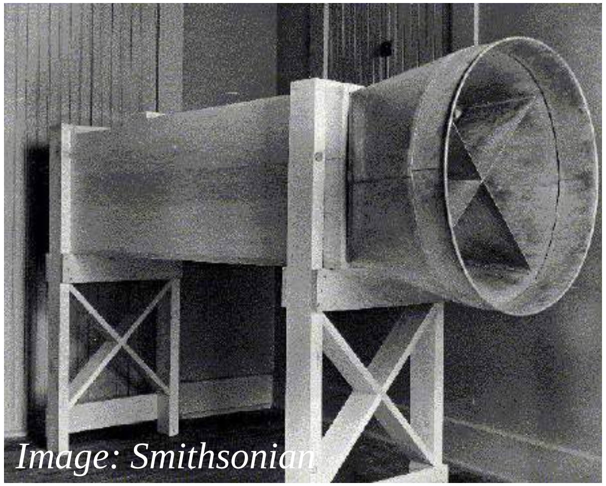


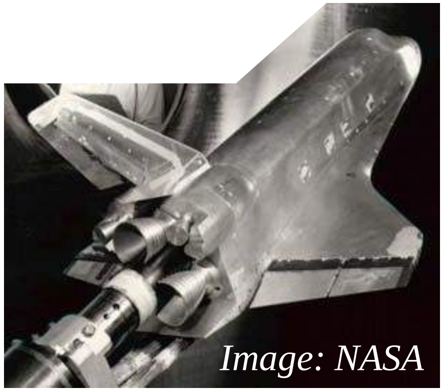
ESP Modeling – Physical Models

- Background
- Theory
- Simulation Parameters
- Fabrication Details
- Results Analysis
- Flow Visualization

Physical Models – Background

- Utilized for fluid flow analysis for a century … or more?
- Applied to ESPs for decades
- Underlying principle is to reproduce fluid flow behavior in a controlled, laboratory environment





Physical Models – Theory

- Key criteria is to generate "Similarity" between the scale model and the real-world object
  - Geometric similarity
    - Accurate scale representation of geometry
    - Inclusion of all influencing geometry elements
    - Selection of scale can be important
  - Fluid dynamic similarity
    - Precise Reynolds Number (Re) matching is not feasible
    - General practice is to match full scale velocity but ensure that Re remains in the turbulent range throughout the model

$$Re = \frac{\rho \, v \, D_h}{\mu}$$

Physical Models – Parameters

- ESP geometry
  - Typically 1/8th to 1/16th scale
  - Include features affecting flow patterns
- Flow conditions
  - Scaled air flow rate (at ambient temperature)
  - Simulate injections with a tracer gas
  - Simulated particle tracking
    - In flight
    - Deposition

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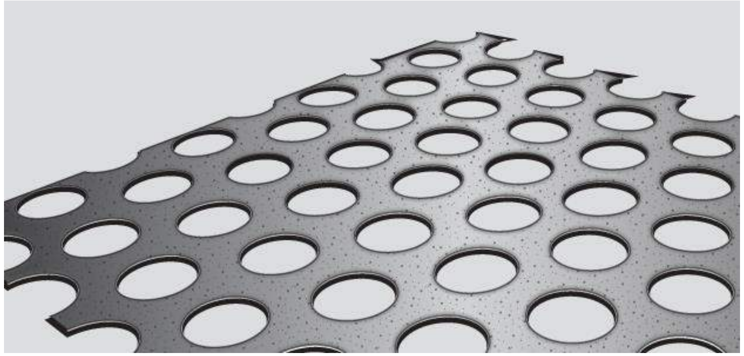
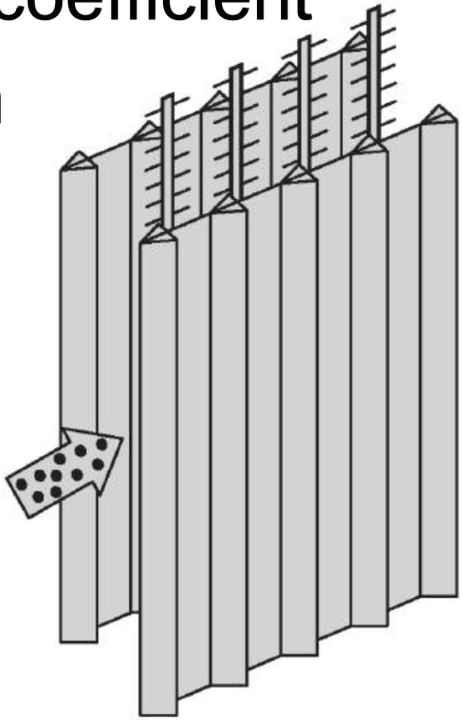
Physical Models – Fabrication Details

❖ More detail is better
  - Vanes, splitters, baffles
  - Trusses, gusset plates
  - Dampers, columns

Physical Models – Fabrication Details

- ❖ Perforated plate selection
- ❖ Collection plate representation
  - Geometry / loss coefficient
  - Re consideration





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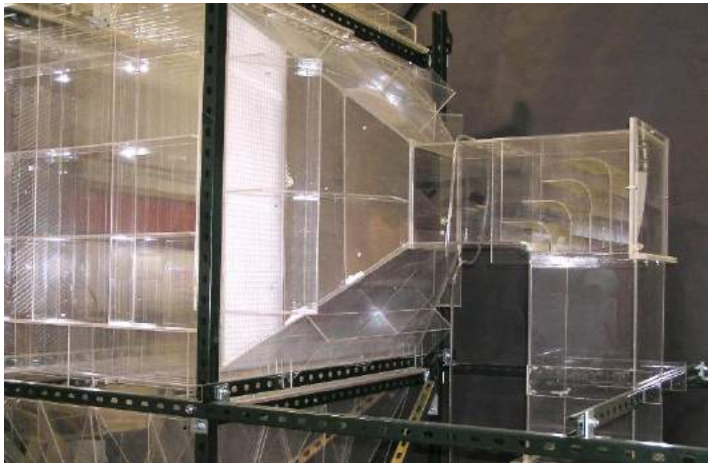
Physical Models – Results Analysis

- Quantitative data
  - Available at discrete measurement points
  - Velocity magnitude, directionality
  - Pressure (corrected to full scale)
  - Tracer gas concentration
  - Mass balance between chambers
  - Comparison to ICAC conditions
  - Correlation to test data



- Qualitative data
  - Flow directionality (smoke, tufts)
  - "Dust Test" for particle behavior, drop-out, re-entrainment

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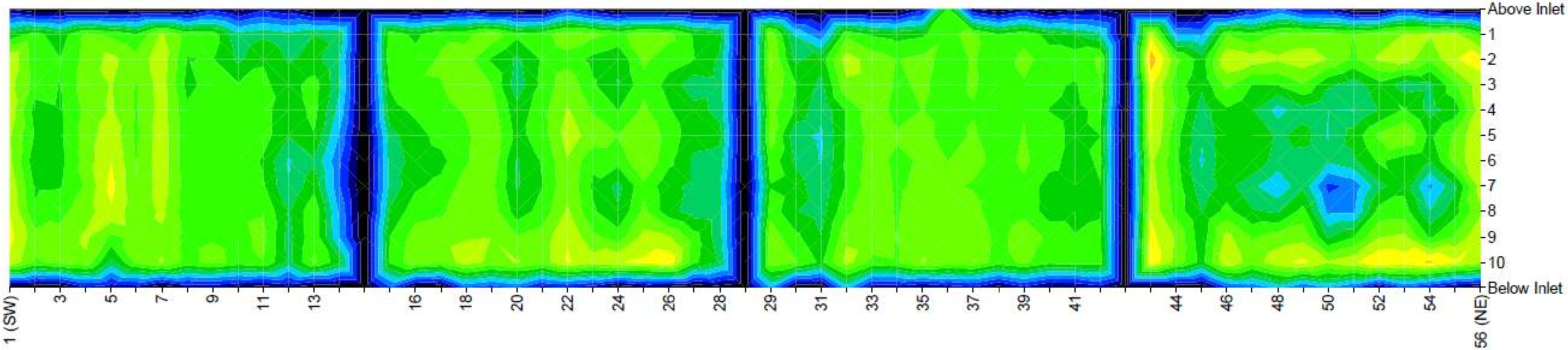
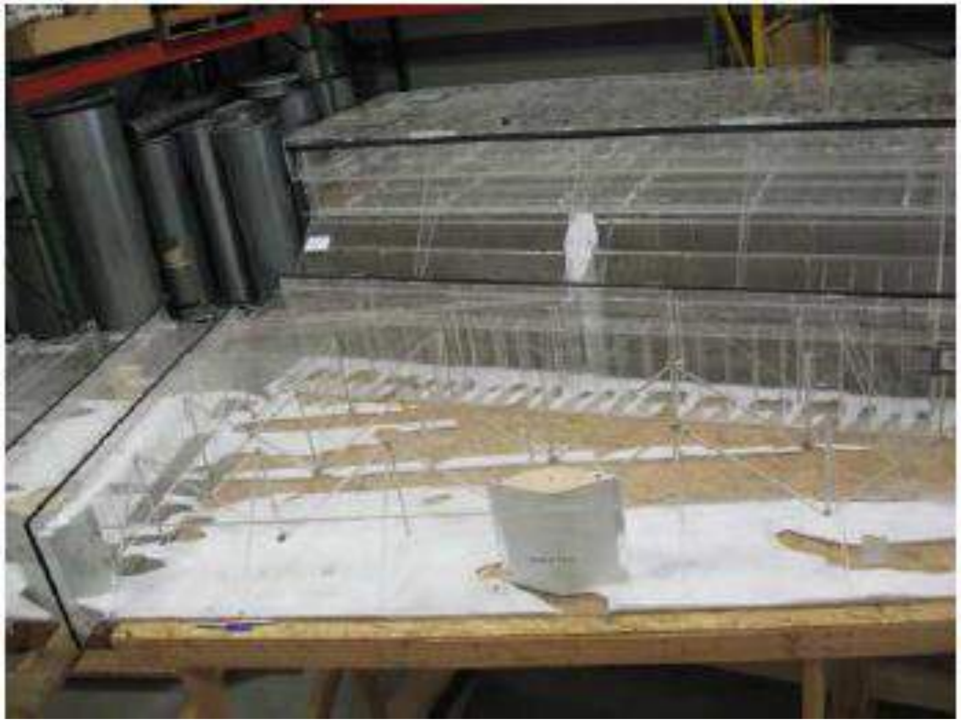
Physical Models – Velocity Results

❖ Uniformity vs. ICAC goals



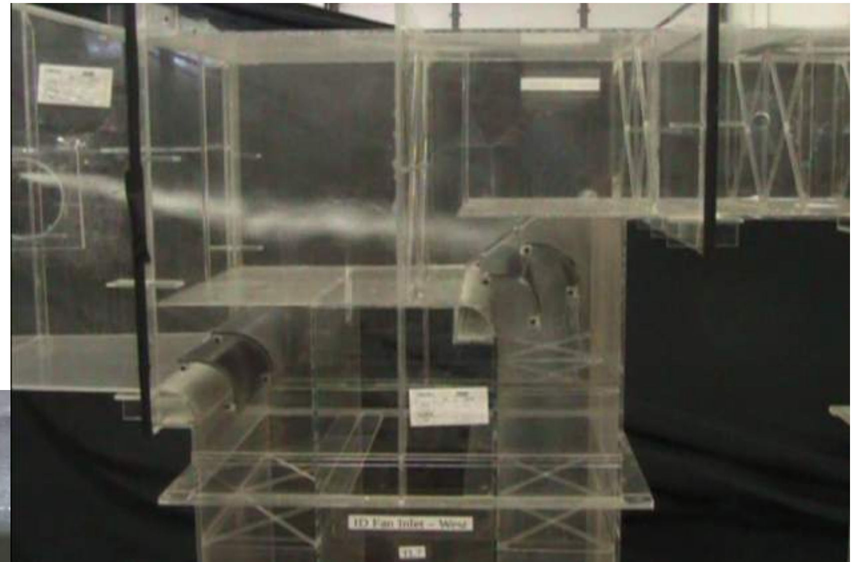
Average Velocity (ft/s):	8.5	
%RMS Uniformity:	12.1%	(Target: <15%)
% of points <115% of average:	90.7%	(Target: >85%)
% of points <140% of average:	100.0%	(Target: >99%)
% of lower 25% of area >71% of average:	100.0%	(Target: >99%)

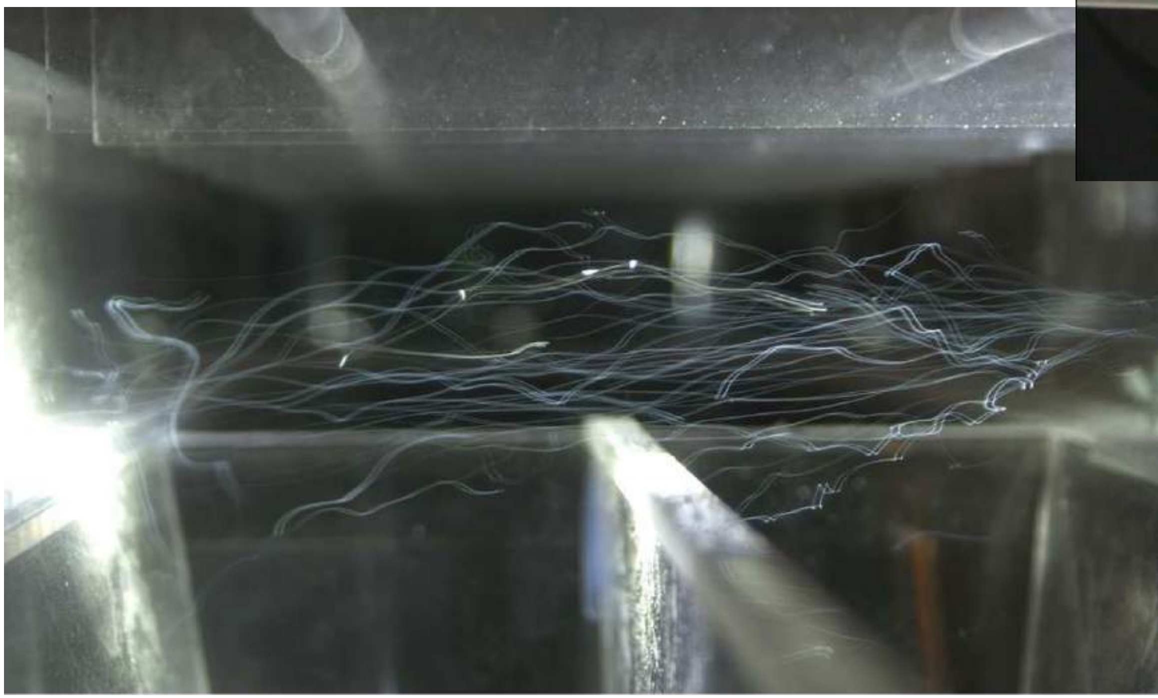
Physical Models – Dust Testing



Physical Models – Visualization

- Smoke flow
- Helium bubbles





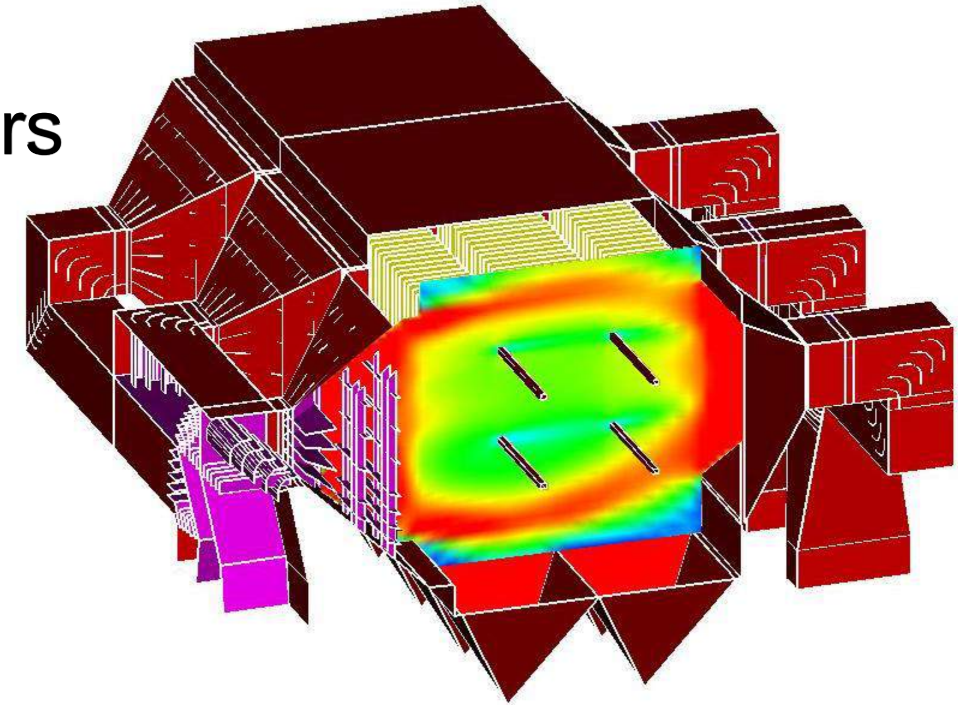
Images: Gerry Klemm, Southern Company

Physical Models – Visualization

- Video footage

ESP Modeling – CFD

- Background
- Theory
- Simulation Parameters
- Mesh Details
- Results Analysis
- Flow Visualization



CFD – Background

- Developed in the aerospace industry c.1970 (with the advent of “high speed” computers)
- Applied to ESPs for 30+ years
- Underlying principle is to solve the first-principles equations governing fluid flow behavior using a computer

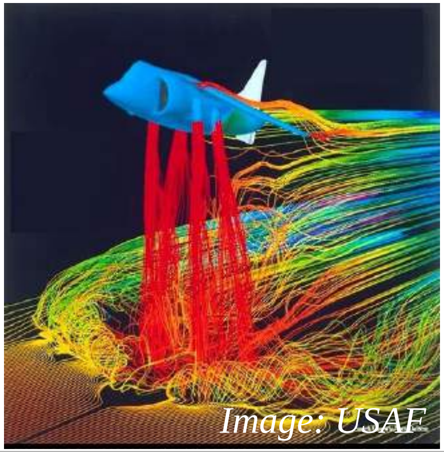
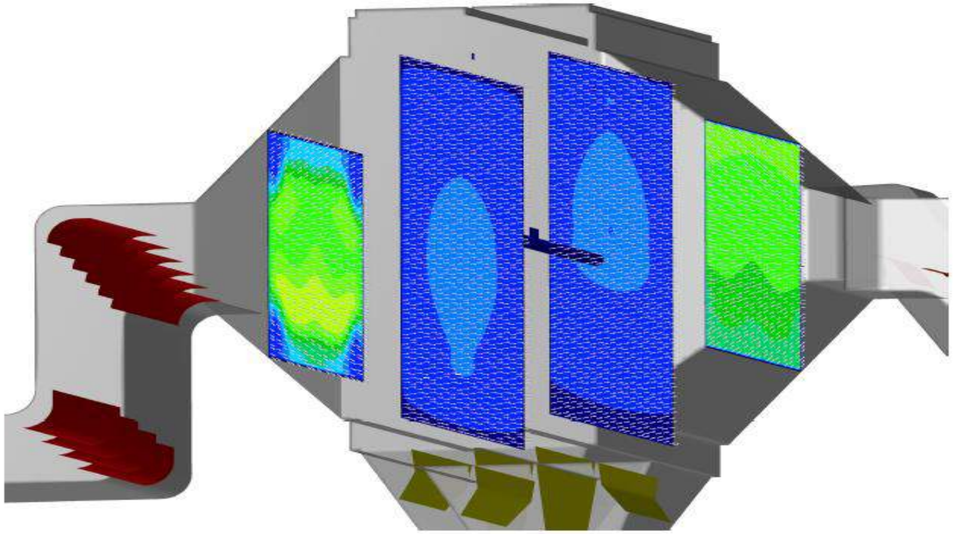


Image: USAF



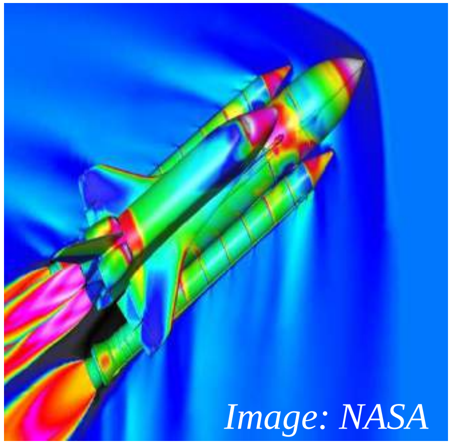
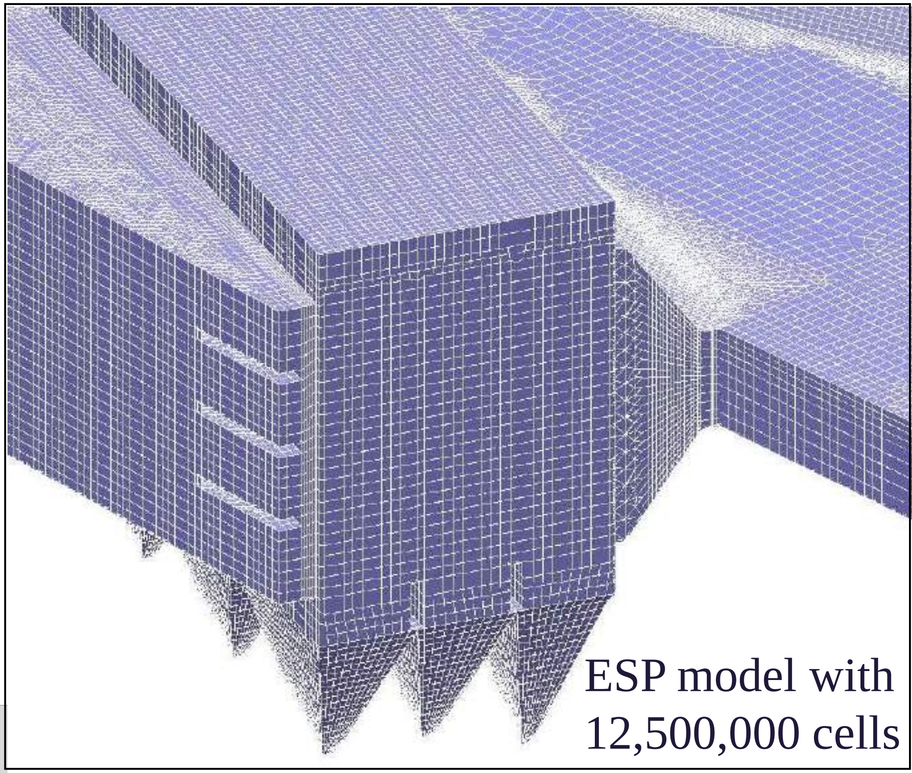


Image: NASA

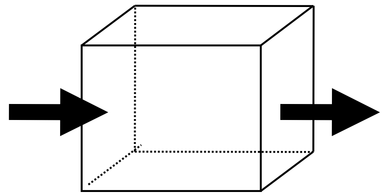
CFD – Theory

❖ Control Volume Approach

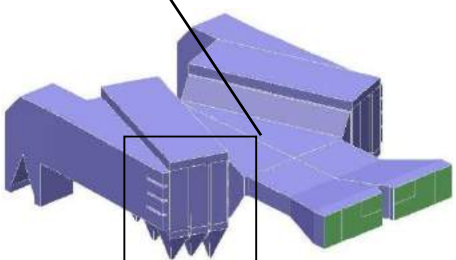
- Divide the flow domain into distinct control volumes
- Solve the Navier-Stokes equations (Conservation of Mass, Momentum, Energy) in each control volume



ESP model with
12,500,000 cells

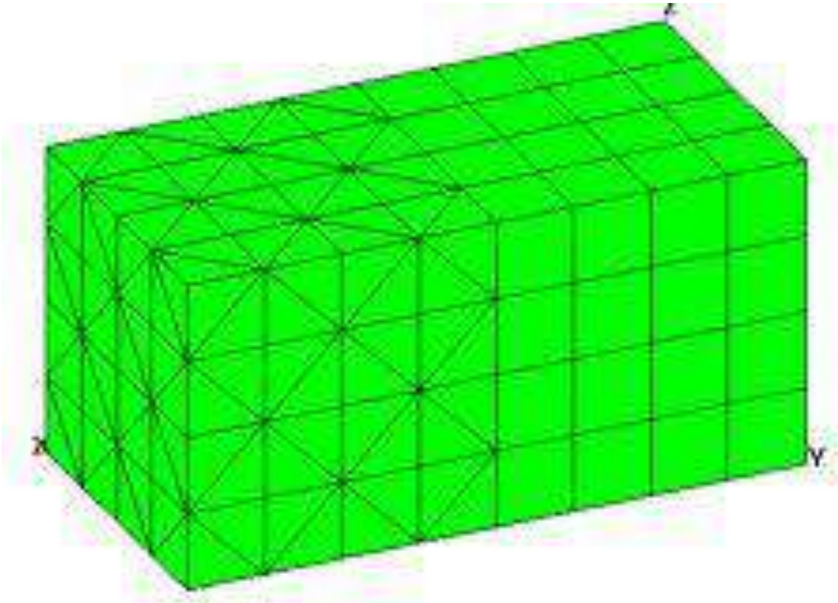


Control Volume or "Cell"



CFD – Mesh Details

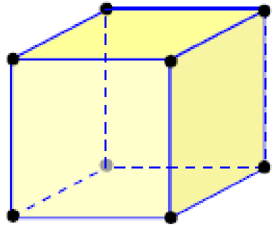
- A good mesh is critical for accurate results
  - Cell count
  - Length scale
  - Local refinement
  - Shape/topology
    - Hex vs. Tet vs. Poly
  - Flow alignment



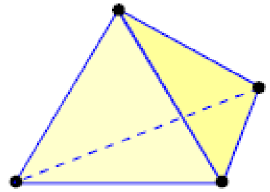
- Why?
  - Finer resolution = more accurate results
  - Numerical calculation scheme accuracy is influenced by cell topology

CFD Mesh Quality – Cell Topology

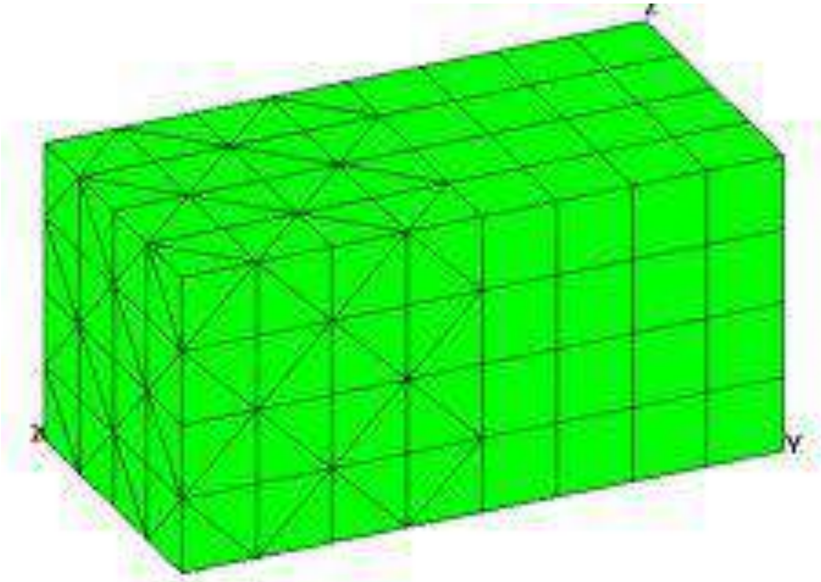
- Not all CFD cells are created equal
  - Hexahedral vs. Tetrahedral vs. Polyhedral
  - Tet mesh = easier, automeshing
  - Hex or hybrid mesh = harder, hand built
  - 5 million Hex cells = 30 million Tet cells



Hexahedral cell
(6 faces)



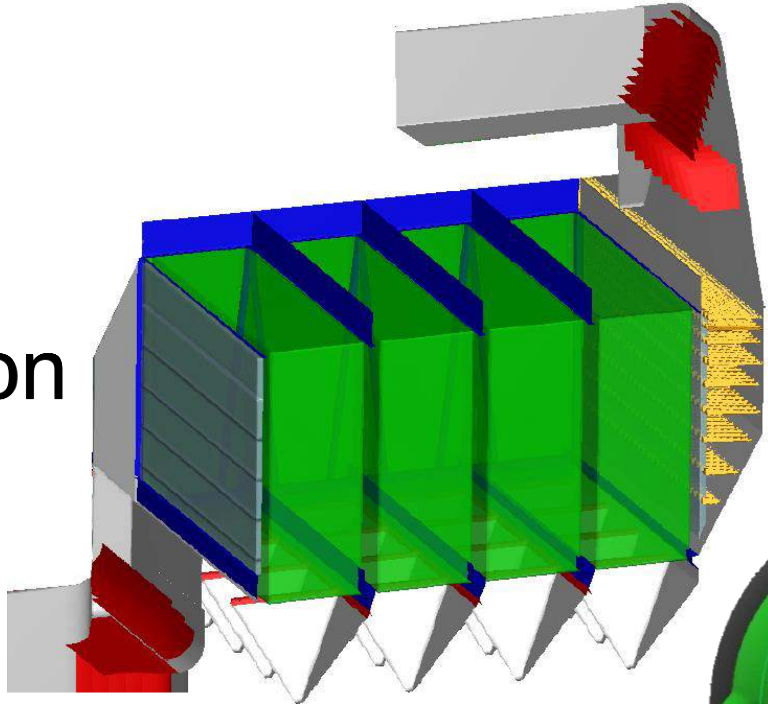
Tetrahedral cell
(4 faces)

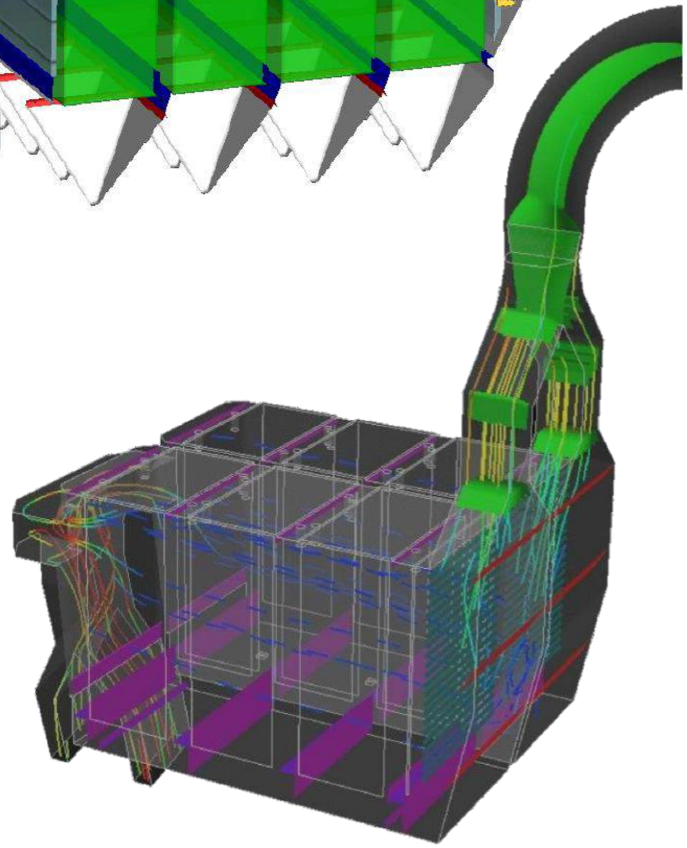


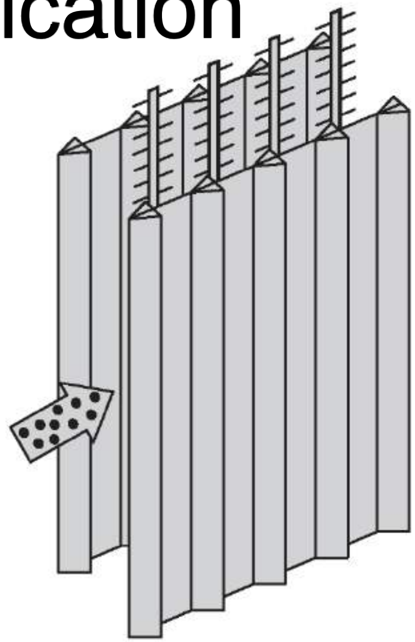
6 Tet cells fit into 1 Hex cell
of the same length scale

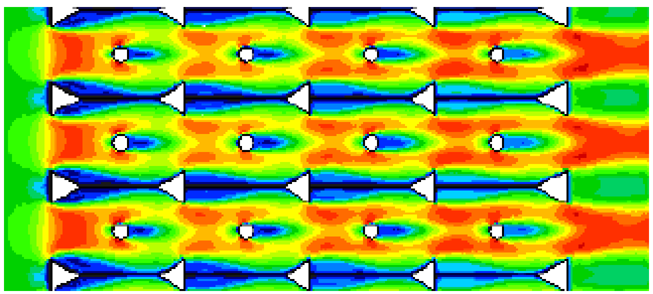
CFD – Mesh Details

- Direct geometry inclusion
  - Vanes, baffles
  - Structure
- Numerical simplification
  - Perforated plates
  - Collection plates



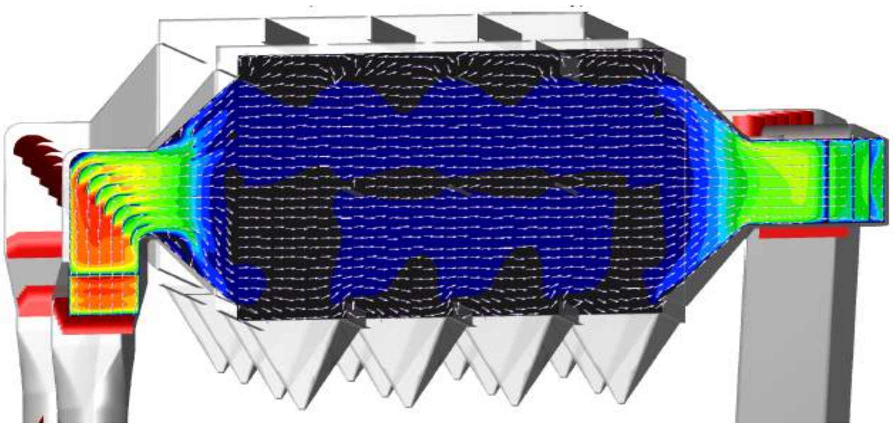






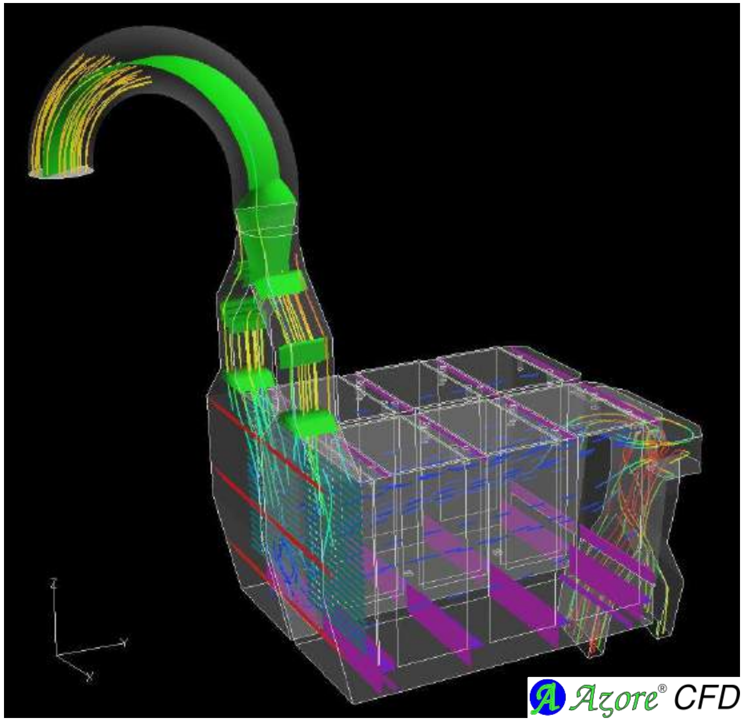
CFD – Simulation Parameters

- ESP geometry (mesh)
  - Full scale representation
  - Include features important to flow, more detail if possible
- Flow conditions
  - Full scale gas flow rate
  - Reproduce velocity & temperature profile at model inlet
  - Simulated chemical injection
  - Simulated particle tracking
- Solver
  - Azore
  - Fluent
  - Star CCM+



CFD – Results Analysis

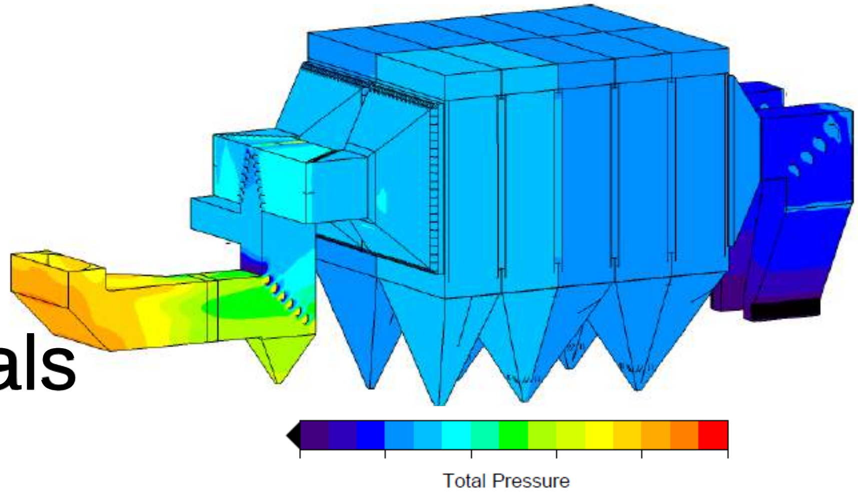
- Quantitative data available at all control volumes
  - Velocity magnitude, directionality
  - Temperature
  - Pressure
  - Turbulence
  - Chemical species concentrations
  - Particle trajectories

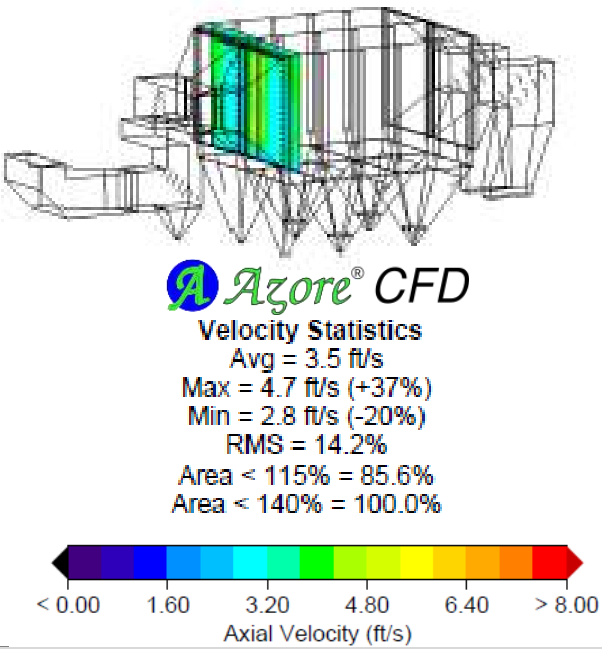


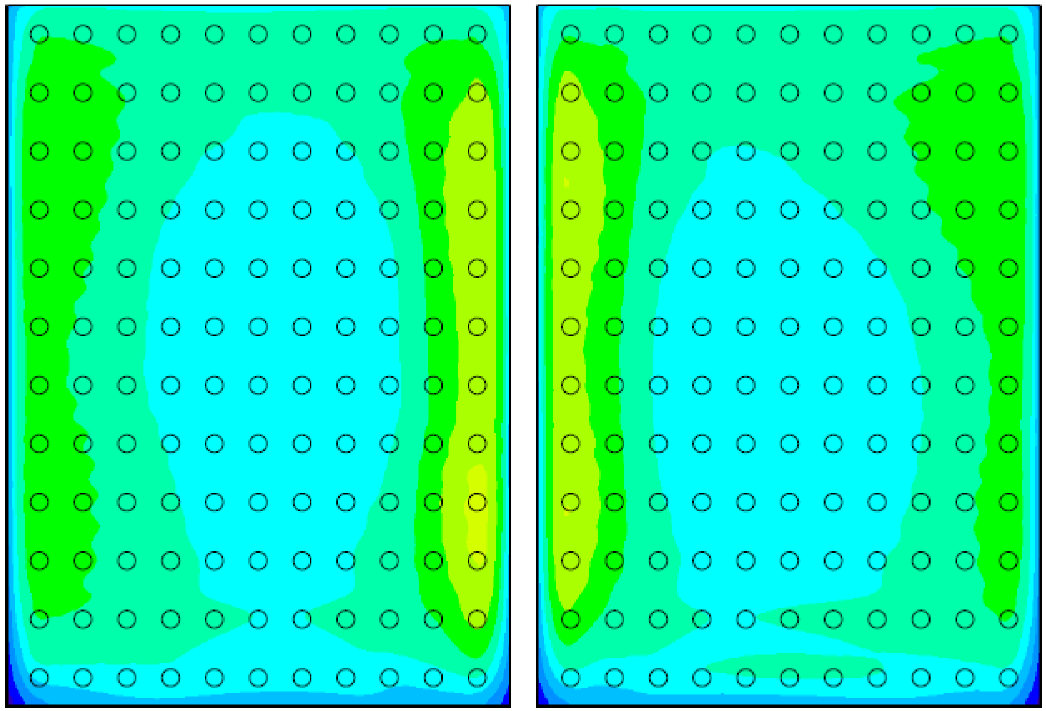
- Integrated/reduced data
  - Mass balance between chambers
  - Comparison to ICAC conditions
  - Correlation to test data

CFD – Results

- Velocity patterns
- Uniformity vs. ICAC goals
  - All cells vs. traverse
- Pressure drop







% Flow to West Chamber = 50.1%

% Flow to East Chamber = 49.9%

CFD – Advanced Modeling

- Electrostatics
- Transient phenomenon
- Large meshes and HPC solvers
- Pressure pulses during to rapping
  - Hopper “splash”
  - Minimizing re-entrainment
- Chemistry / absorption

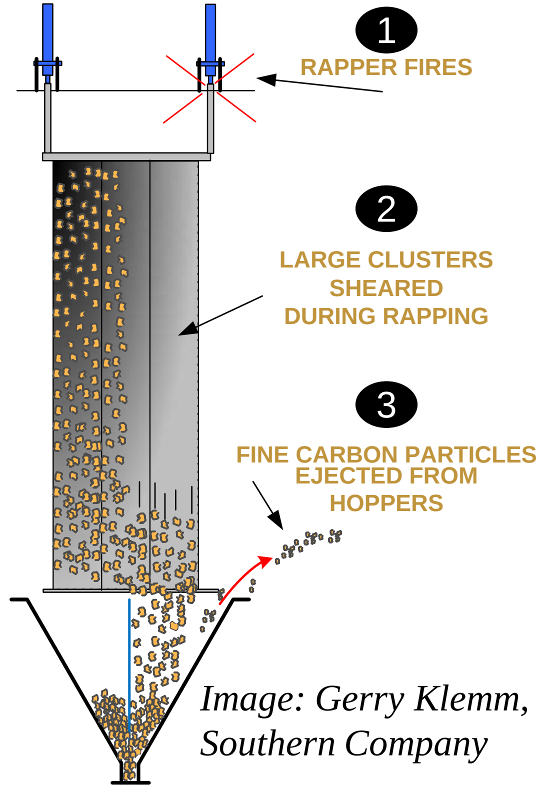
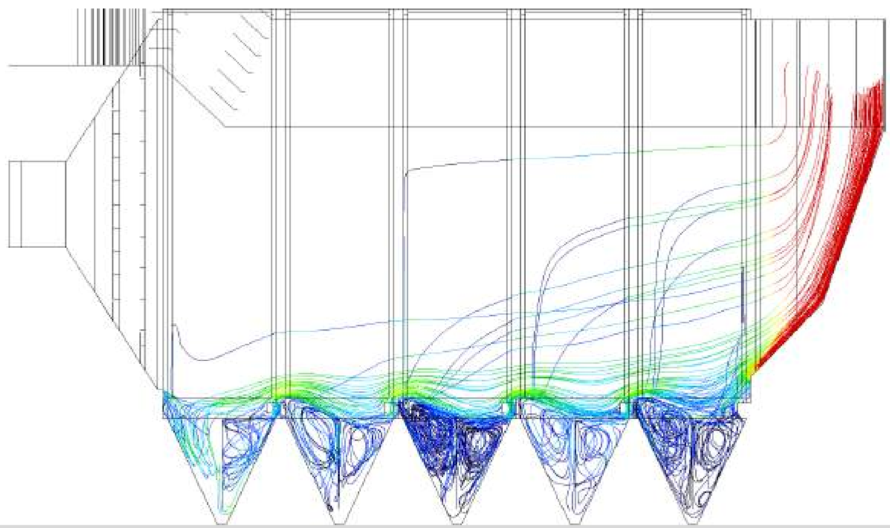


Image: Gerry Klemm, Southern Company



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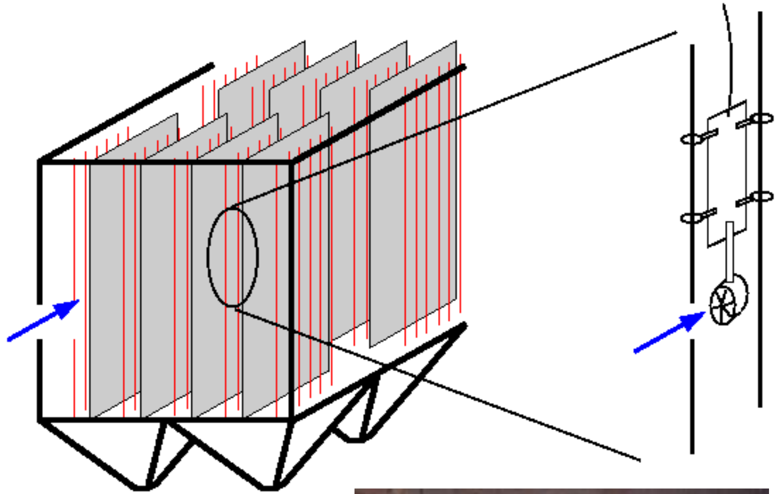
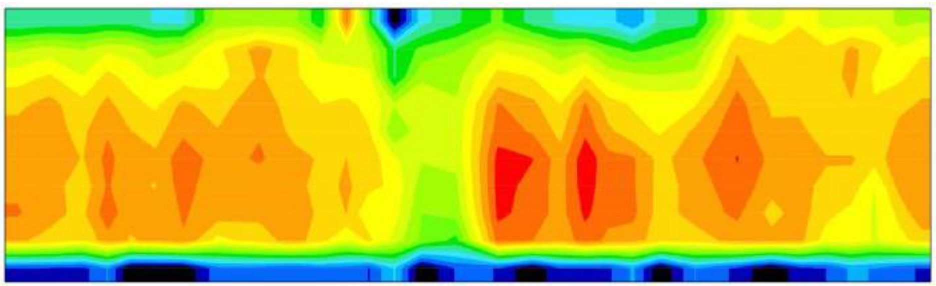
CFD – Flow Animations

- Video footage

Model Correlation – Field Testing

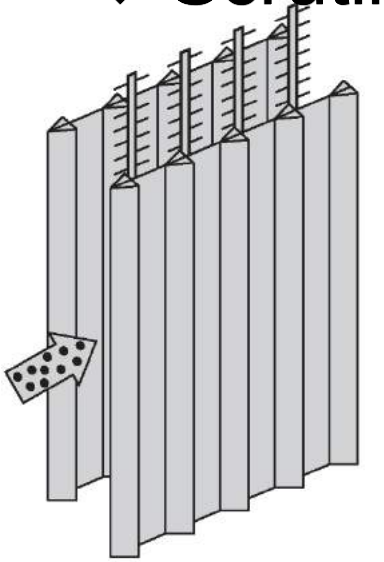


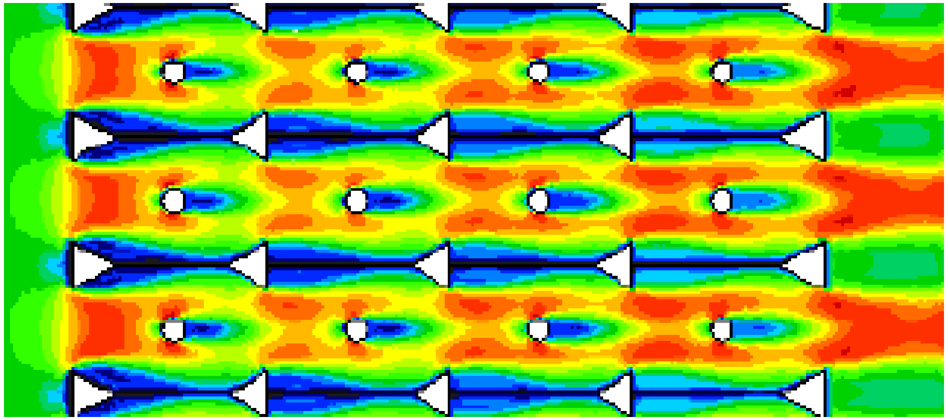
- Velocity Distribution in ESP
  - Cold flow conditions
  - Vane anemometer
    - Rides on plates / electrodes
    - Accuracy **1%** in 3-10 ft/sec range
    - Lightweight, portable
    - Sensitive to flow angularity, turbulence, dust
  - Difficult, expensive test

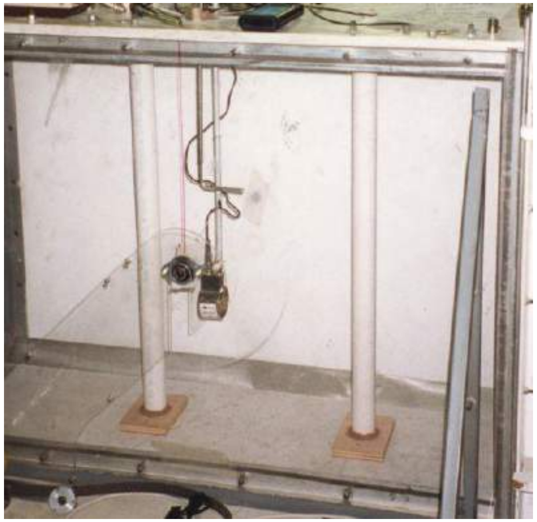


Field Testing – Collection Region

- Accuracy can be influenced by
  - Proximity to perforated plate
  - Collection plate geometry
  - Electrode geometry
- Scrutinize the test data closely







Flow Model Accuracy

- Do physical and CFD models provide useful results, suitable for ESP design?
  - Yes, experience has shown that modeling is a dependable engineering tool
  - Useful for new ESPs and improving existing ESPs
  - Needs to be performed correctly and to the best of current modeling practices

Flow Model Accuracy

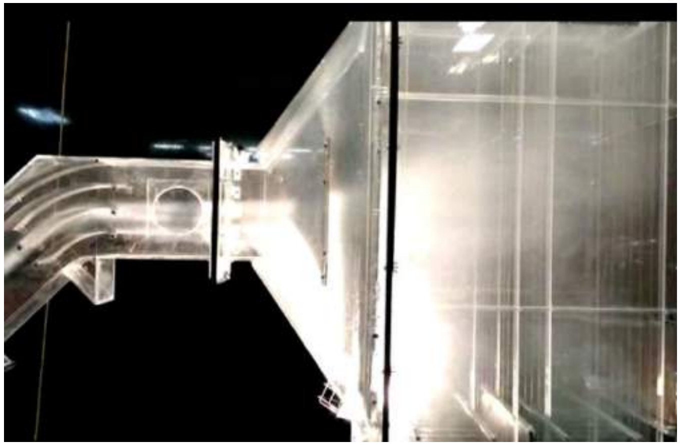
- Do the model results match actual plant data?
  - Not as well as one would like in some cases
  - Error bars are larger than desired
  - Correlation can be dependent on ESP geometry
    - Nozzle style inlets are particularly challenging for models
    - Square and ladder vane style inlets have stronger correlation
- What to do when they don't match?
  - Re-evaluate the modeling, improve the methods
  - Scrutinize the test data

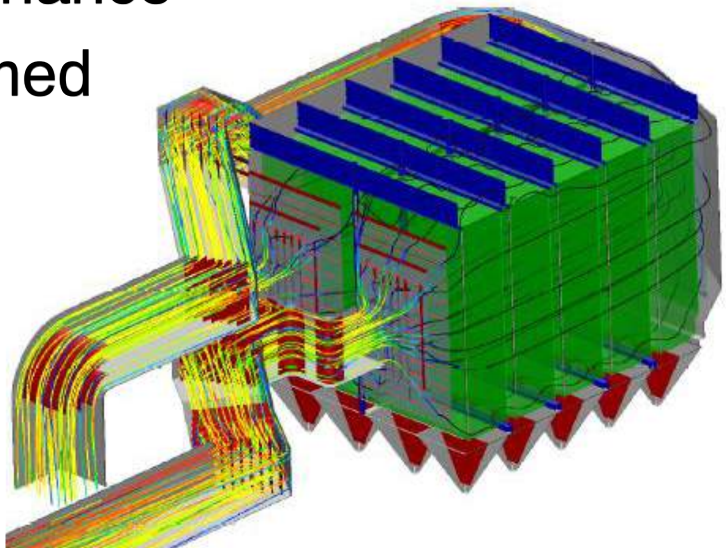
Flow Model Accuracy

- ❖ Do CFD and physical models match each other?
  - Sometimes but not all
  - Correlation of uniformity statistics vs. profile
  - Limitations of both methods hamper correlation
  - Can be dependent on ESP geometry
    - ➢ Inlet style – nozzle vs. square
    - ➢ Flow devices and complexity
  - Research is ongoing
  - Speaker's experience in this area focuses on
    1. Perforated plate representation
    2. Collection plate representation

Summary – Industry Experience

- Hundreds of successful projects industry wide
  - Performance guarantees met
  - Reduced emissions / DP / maintenance
  - Field verification not often performed





- Improved modeling methods would allow for additional ESP performance optimization

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Summary – Key Takeaways

- Both CFD and physical modeling have been widely used for decades
- From a general view, the modeling methods provide beneficial engineering tools for design
- Both methods have specific procedures, and need to be done correctly to yield usable results
- Both methods have their limitations, their supporters, and their critics
- Research is ongoing on both methods, striving to improve accuracy and correlation

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Questions?

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