Scale-Model Smokestack Simulator (SMSS)

A Facility to Study CEMS and RATA Flow Measurements

Measurement Challenges and Metrology for Monitoring CO_2 Emissions from Smokestacks Workshop

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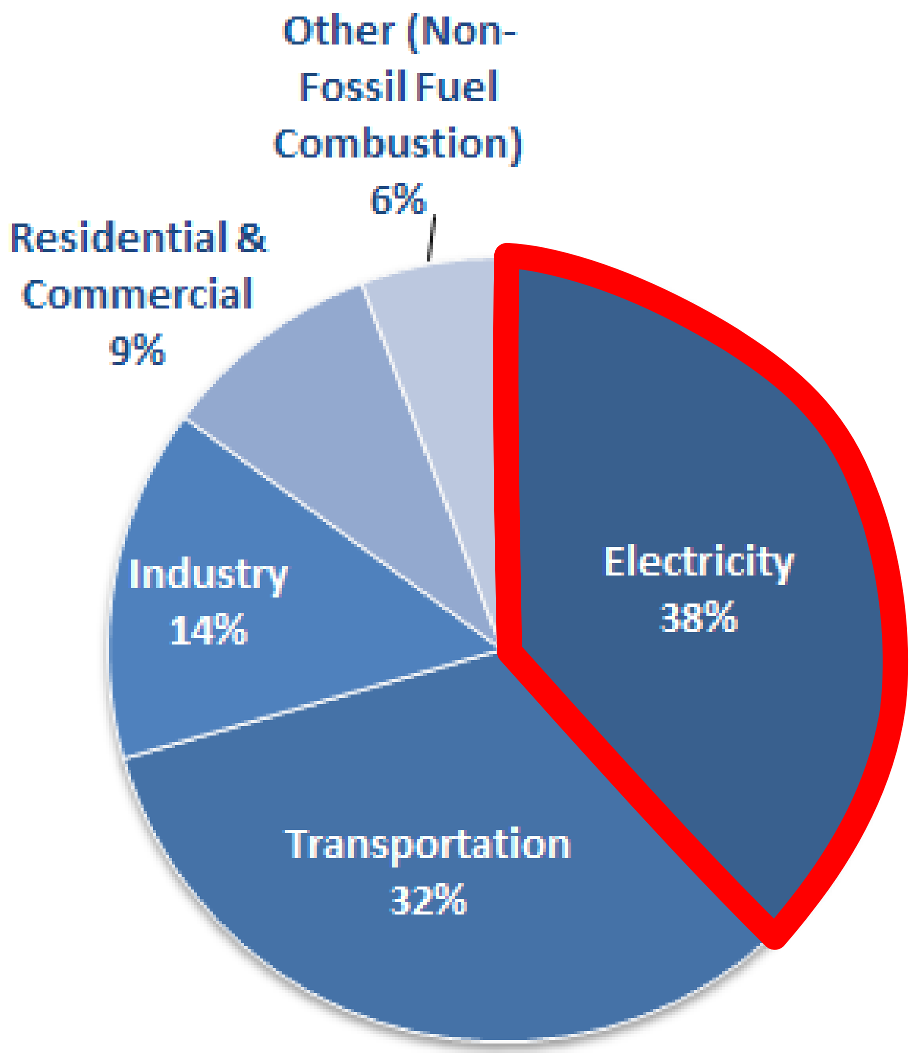
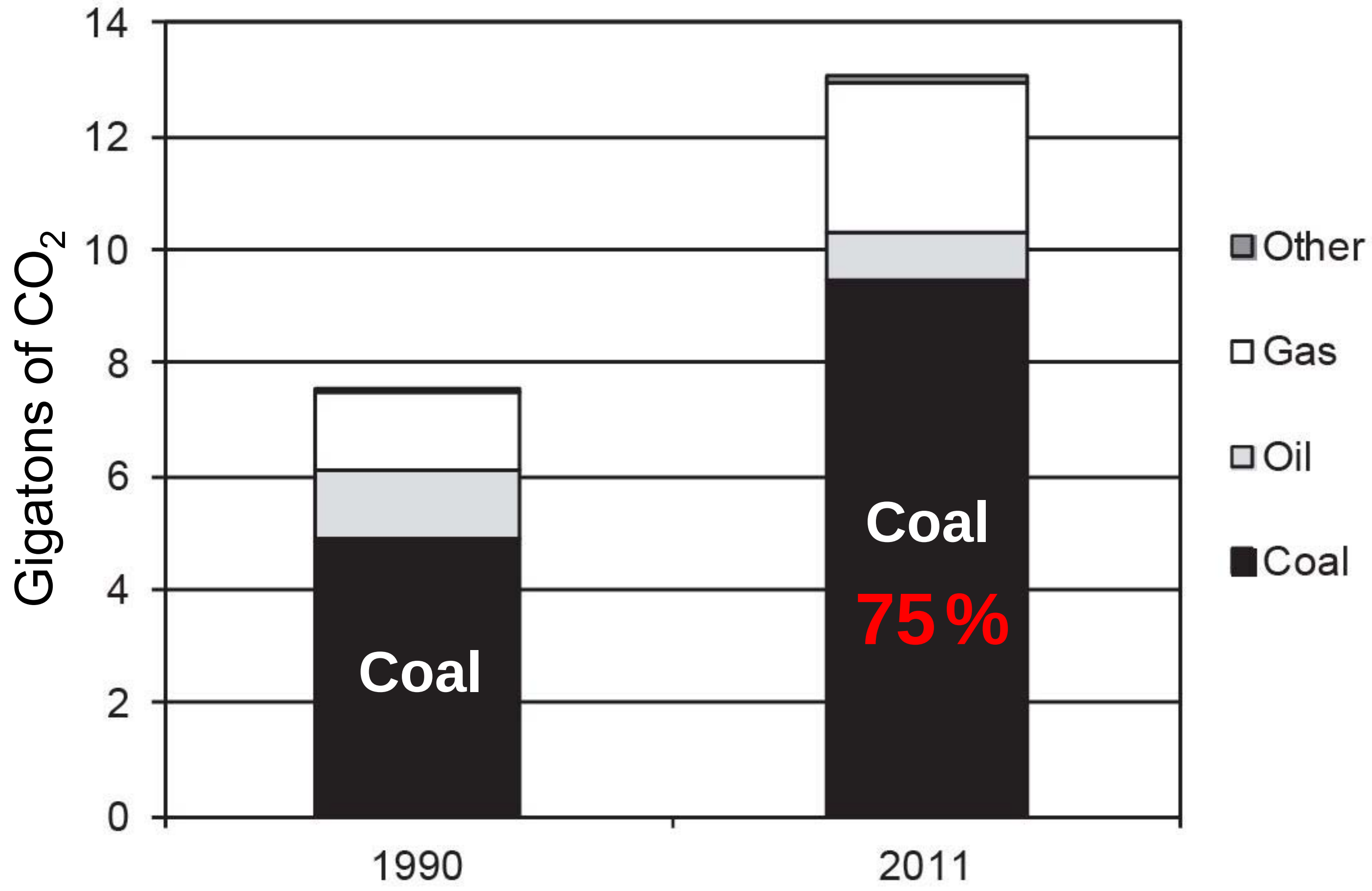
What is the Problem? Why is it Important?



U.S. CO_2 Emissions, by Source (EPA, 2012)

World-Wide, Coal is Most Important, IEA (2013)

Figure 10. CO_2 emissions from electricity and heat generation*

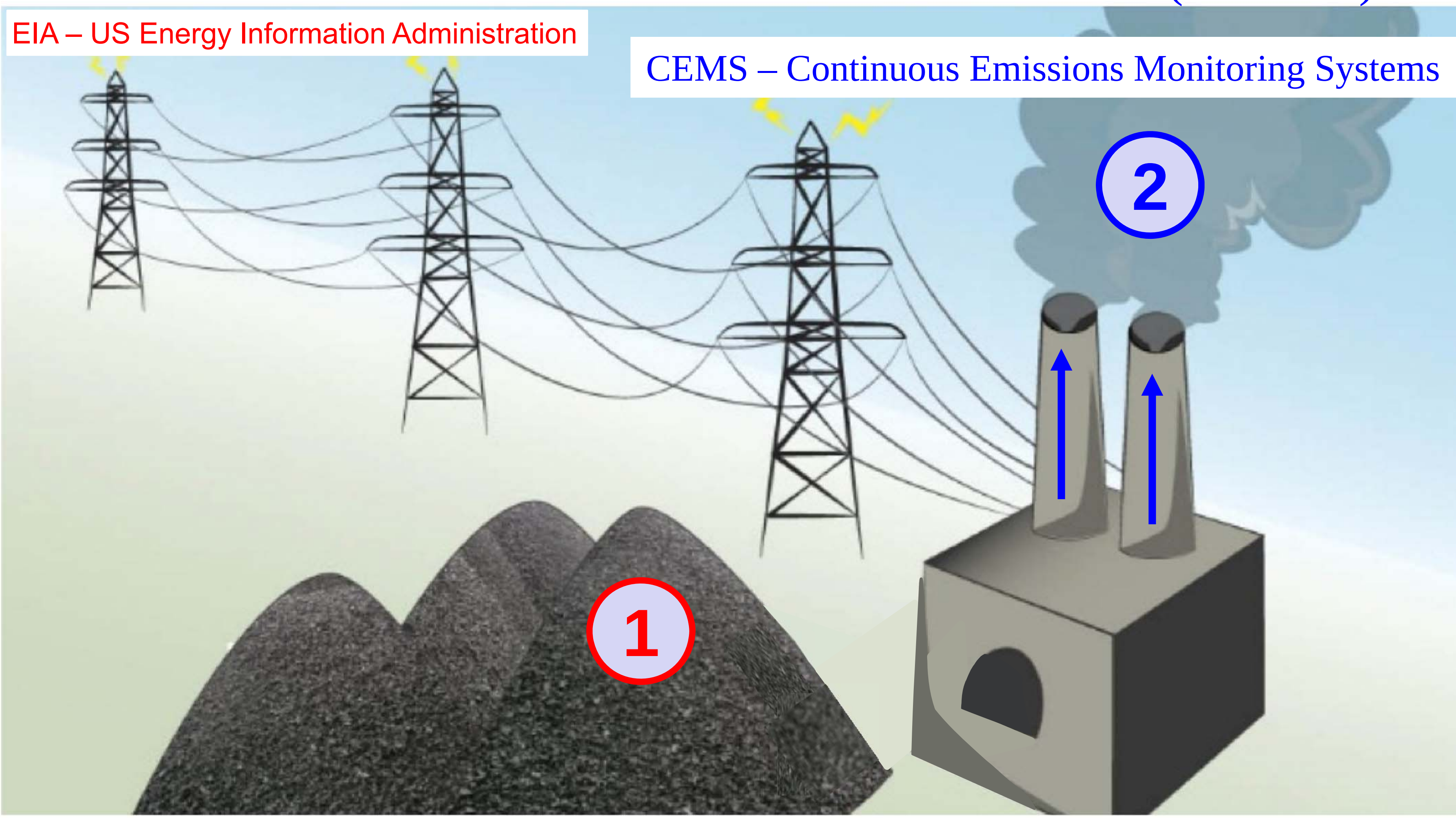


IEA – Internal Energy Agency

Coal-Fired Plants: Two methods to determine CO_2

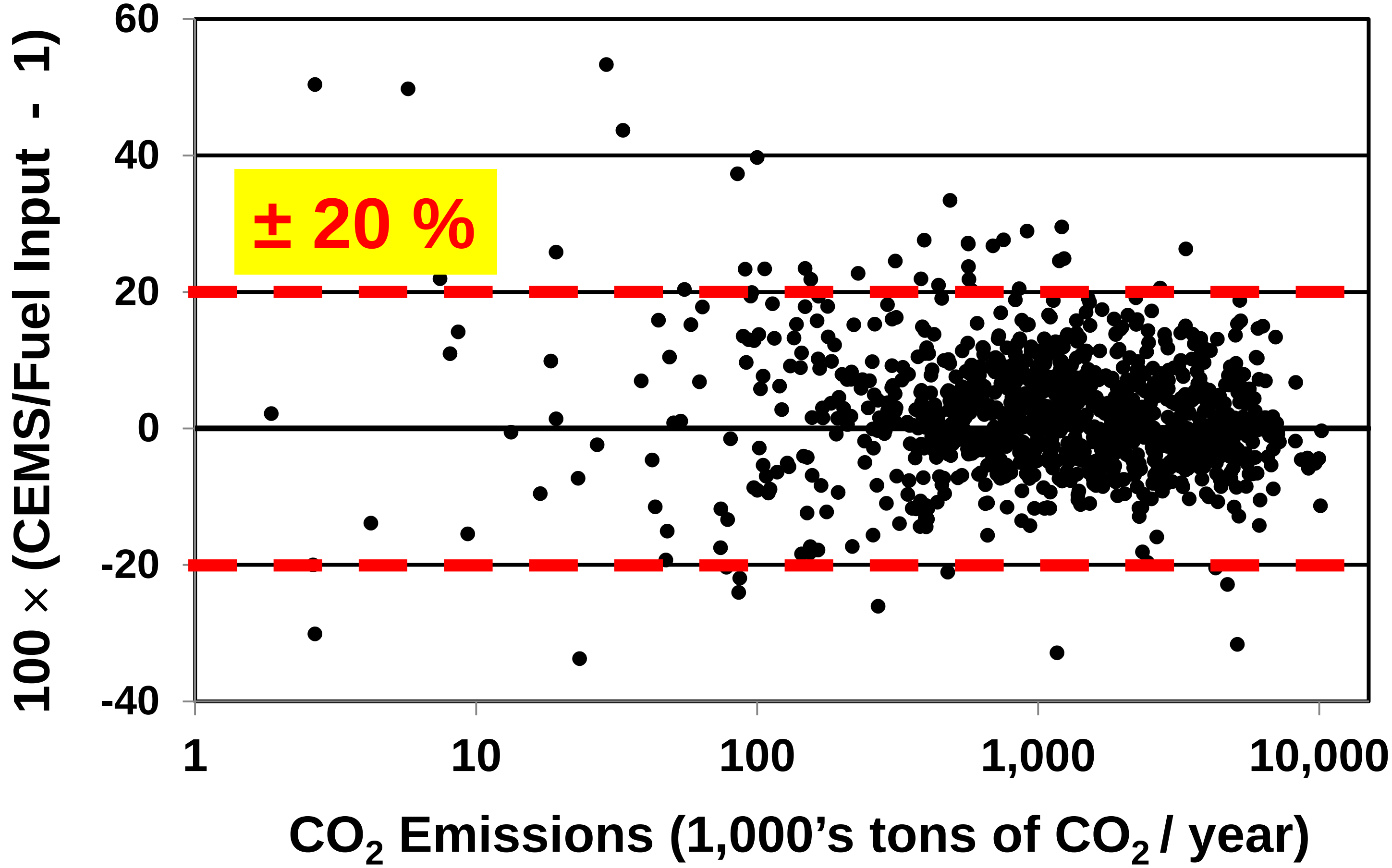
1 ***Fuel Input:***
Amount & quality
of coal (EIA data)

2 ***Emissions Output:***
CEMS - Flow and CO_2
concentration (EPA data)



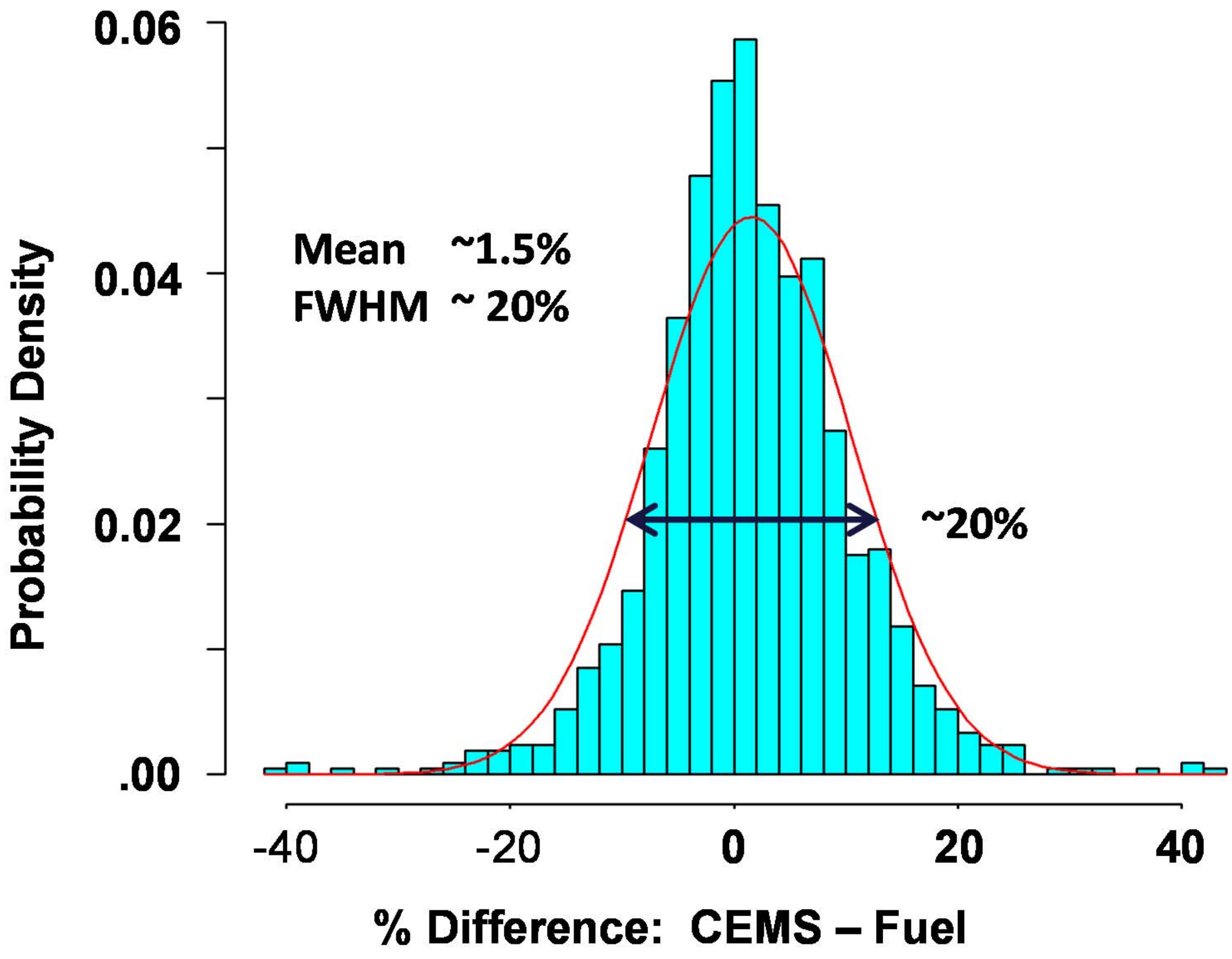
Coal-Fired Plants: CEMS vs. Fuel Input

Do they agree?



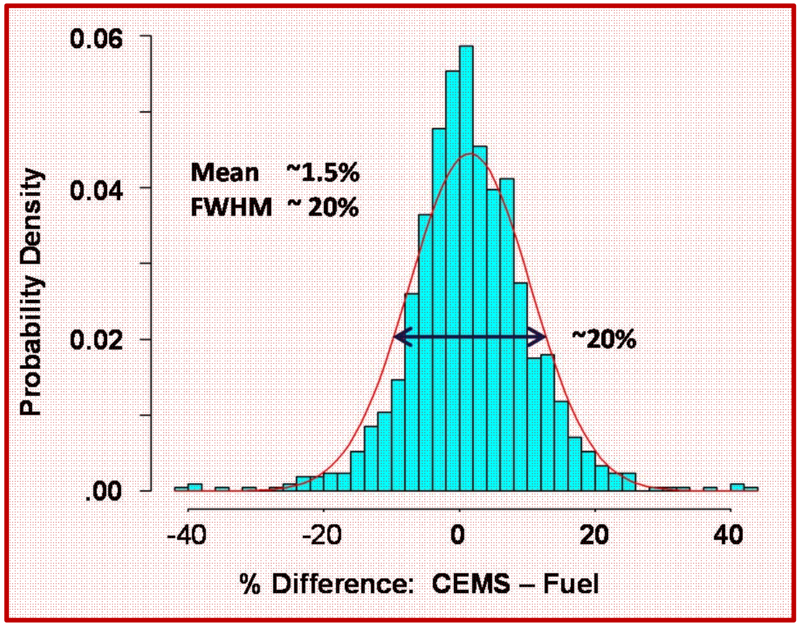
Coal-Fired Plants: CEMS vs. Fuel Input

Do they agree? **No!**



Coal-Fired Plants: CEMS vs. Fuel Input

Do they agree? **No!**



- Disagreement of ± 20 %
- Neither method traceable to the SI
- **Uncertainty is unknown** for either method
- **CEMS method has more potential for improvement**
  - Fuel input method relies on accurate coal emission factors
  - Coal is heterogeneous and quality can vary significantly even within the same lot
- Based on large dispersion there is an effort to determine uncertainty of CEMS

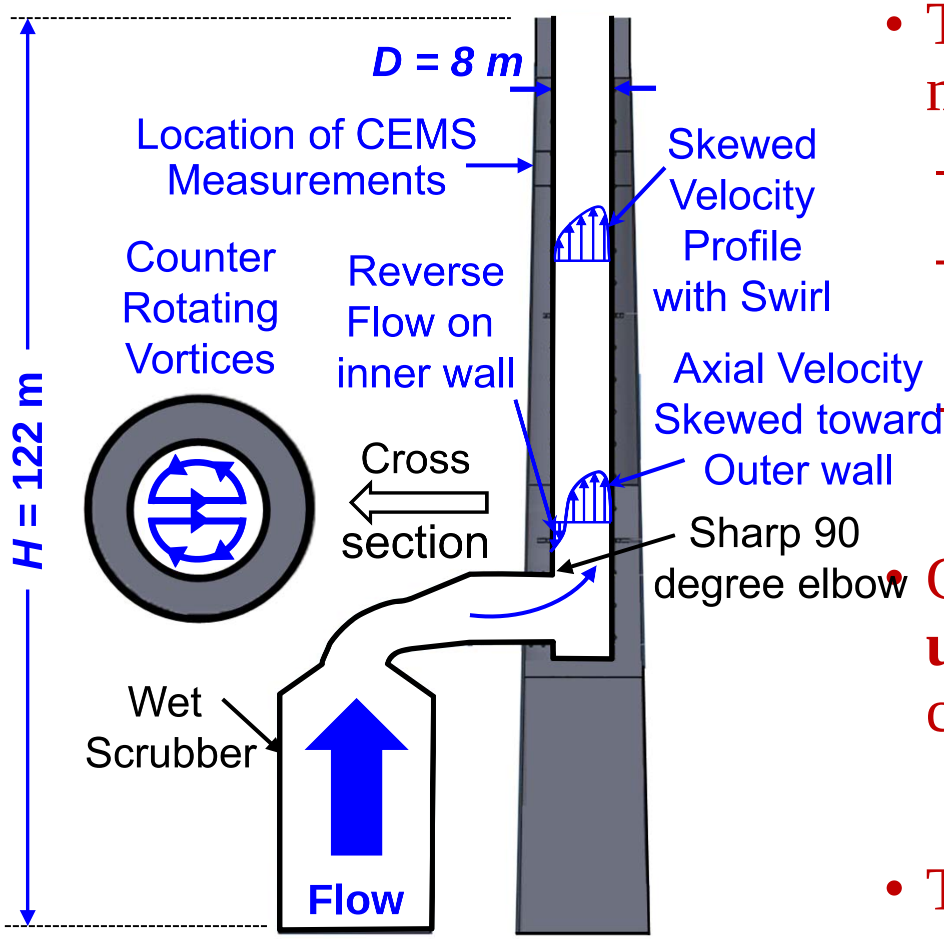
Why are Emissions Measurements Difficult?

- **High Reynolds number ~** 10^7; too large to be reproduced in lab.
- **Flow is fast:** 6 m/s to 26 m/s
- **Nasty conditions:**
  - **Access via outside cat-walk 90 m (300 ft) above ground on older stacks**
  - **Noisy**
  - **Gas is either "hot" (no scrubber 90+ °C) or "ambient & raining" (scrubber)**
  - **Gas is asphyxiating: composition (by volume)**

    13.7 % CO_2
    3.4 % O_2
    74.8 % N_2
    8.0 % H_2O
- **Stacks are big:** no lab can calibrate a 10 m diameter flow meter
- **Flow is complicated**

Flow is Complicated

(Flow Dynamics in a Typical Smokestacks)



Typical Smokestack

- The velocity field at the CEMS measurement location is complicated
  - Skewed velocity profile
  - Swirling flow (*i.e.*, non-zero transverse velocity components)
  - Turbulent flow
- Complexity is caused by **non-ideal upstream geometry** (*e.g.*, sharp corner, fans, elbows)
- The complex velocity field **reduces accuracy of CEMS flow measurements**

How are Emissions Measurements Made Today?

1) Using EPA-approved protocols
   - the bulk gas flow is continuously monitored, and
   - the composition is continuously analyzed for O_2, CO, Hg, SO_2, NO_x *to comply with emission controls*

2) The instruments used for 1) comprise the CEMS = Continuous Emissions Monitoring System
   - Typical CEMS use ultrasonic meters (USM) with one or two paths to monitor flow
   - CEMS require calibration

3) Annual "*Relative Accuracy Test Audit*" (RATA) "calibrates" ultrasonic CEMS flow monitors.
   - the flow is surveyed with a S-Probe, that is temporarily installed on the stack.
   - As the name suggests, the RATA provides only relative accuracy, ***not*** necessarily uncertainty relative to primary standards.

Measurement Need

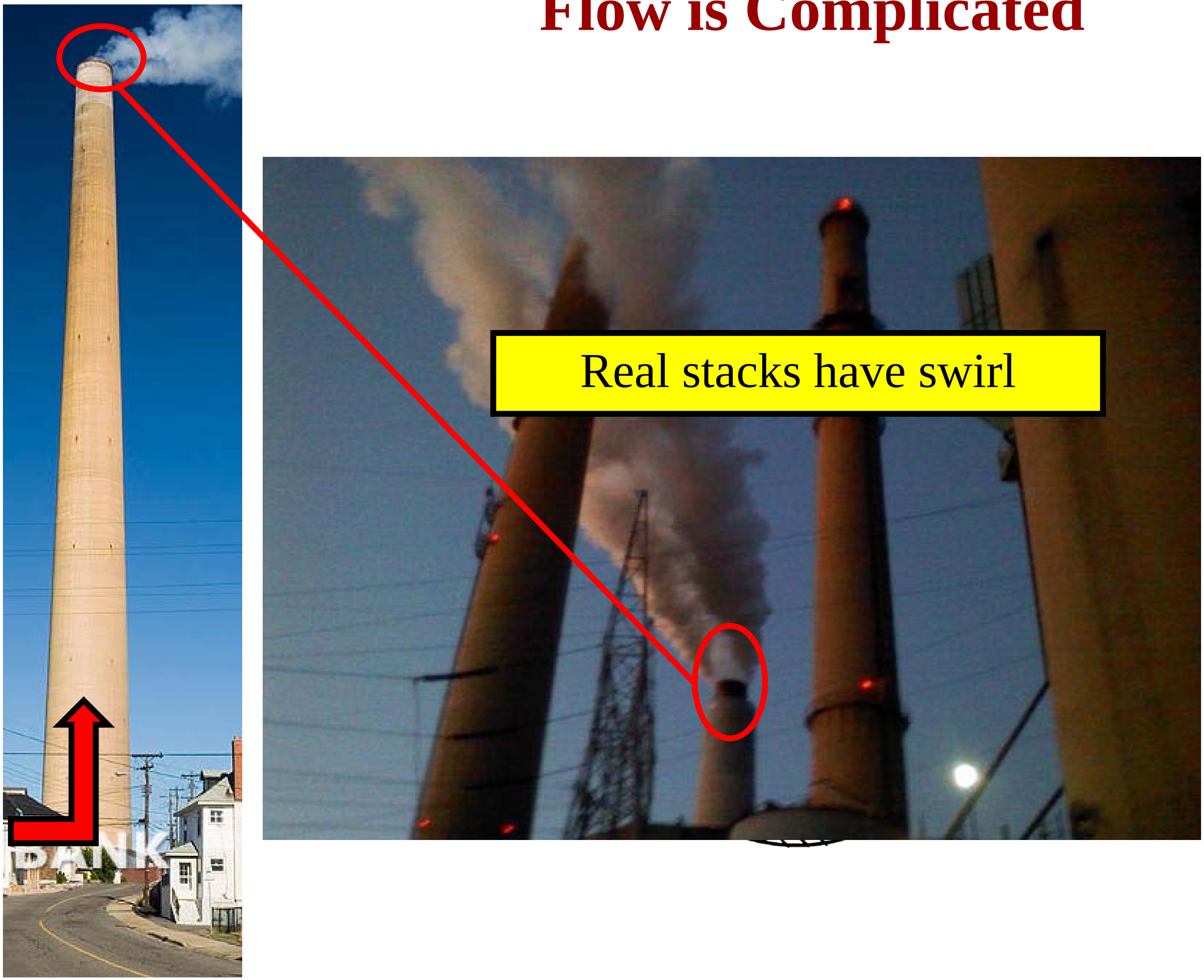
Improve CO_2 measurements from coal-fired power plants

- to **assess** progress of carbon **mitigation efforts** and
- to **fairly implement future carbon controls** (*e.g.*, carbon tax, cap and trade)
- to **provide accurate input data** for climate CO_2 mass balance models

NIST Objective: *SI-traceable,* CO_2 flux measurements with 1 % expanded uncertainty at a reasonable cost

to provide the technical basis for carbon control in the US and internationally

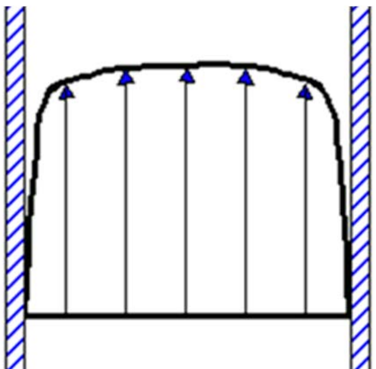
Flow is Complicated



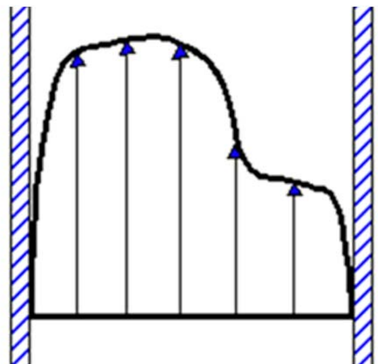
Flow is Complicated

Ideal Profile

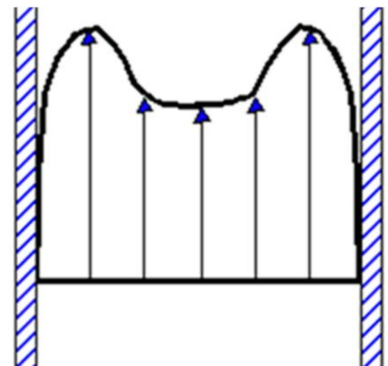
Real stacks have Skew



Fully Developed Turbulent Velocity Profile



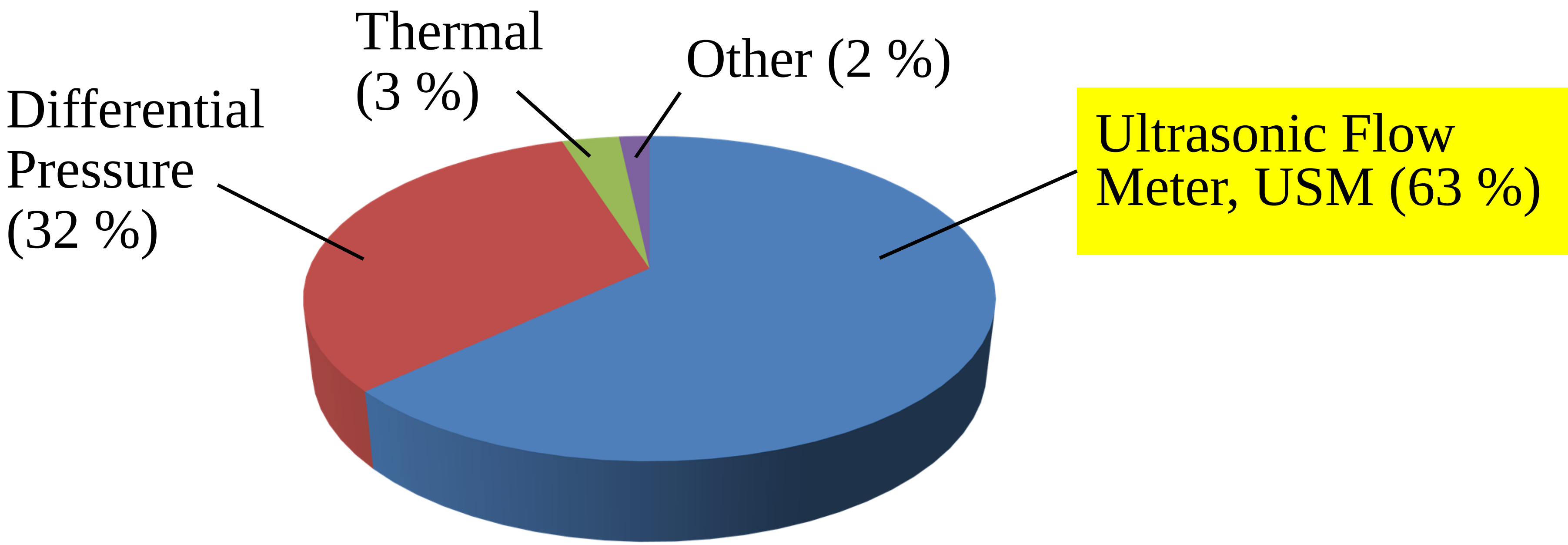
Possible Smokestack Velocity Profile



Possible Smokestack Velocity Profile

Technologies Used for CEMS Flow Measurements

(Flow Monitoring Equipment Installed in Smokestacks)



Ultrasonic Meter (USM) Principle of Operation

- USM transducer emits ***sound beam*** of known frequency
- USM **measures the transit time** of the sound beam to travel a known distance (*L*) **with** and **against** the flow

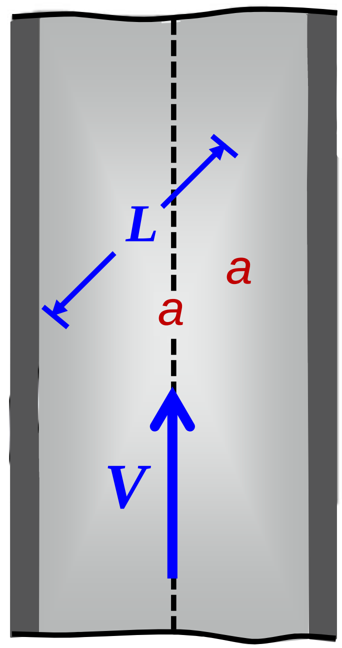
$$t_{\text{with}} = \frac{L}{a + V_L} \qquad t_{\text{against}} = \frac{L}{a - V_L}$$

- Averaged path velocity along path L

$$V_L = \frac{L}{2}\left(\frac{1}{t_{\text{with}}} - \frac{1}{t_{\text{against}}}\right)$$

- The USM determines the **flow velocity** by projecting the path velocity (V_L) onto the flow axis

$$V_{USM} = \frac{V_L}{\cos\theta} = \frac{L}{2\cos\theta}\left(\frac{1}{t_{\text{with}}} - \frac{1}{t_{\text{against}}}\right)$$



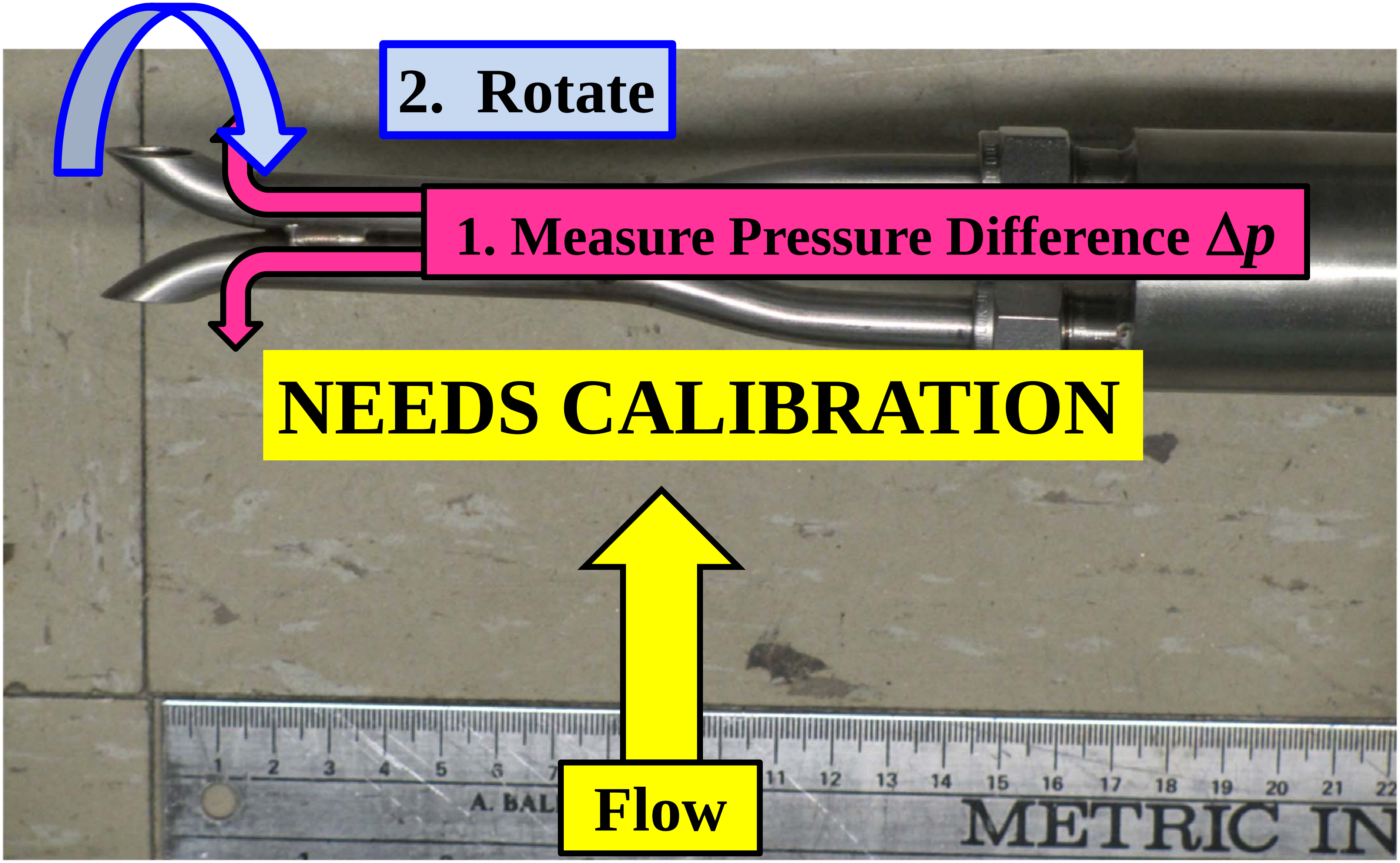
Sender & Receiver

Smokestack

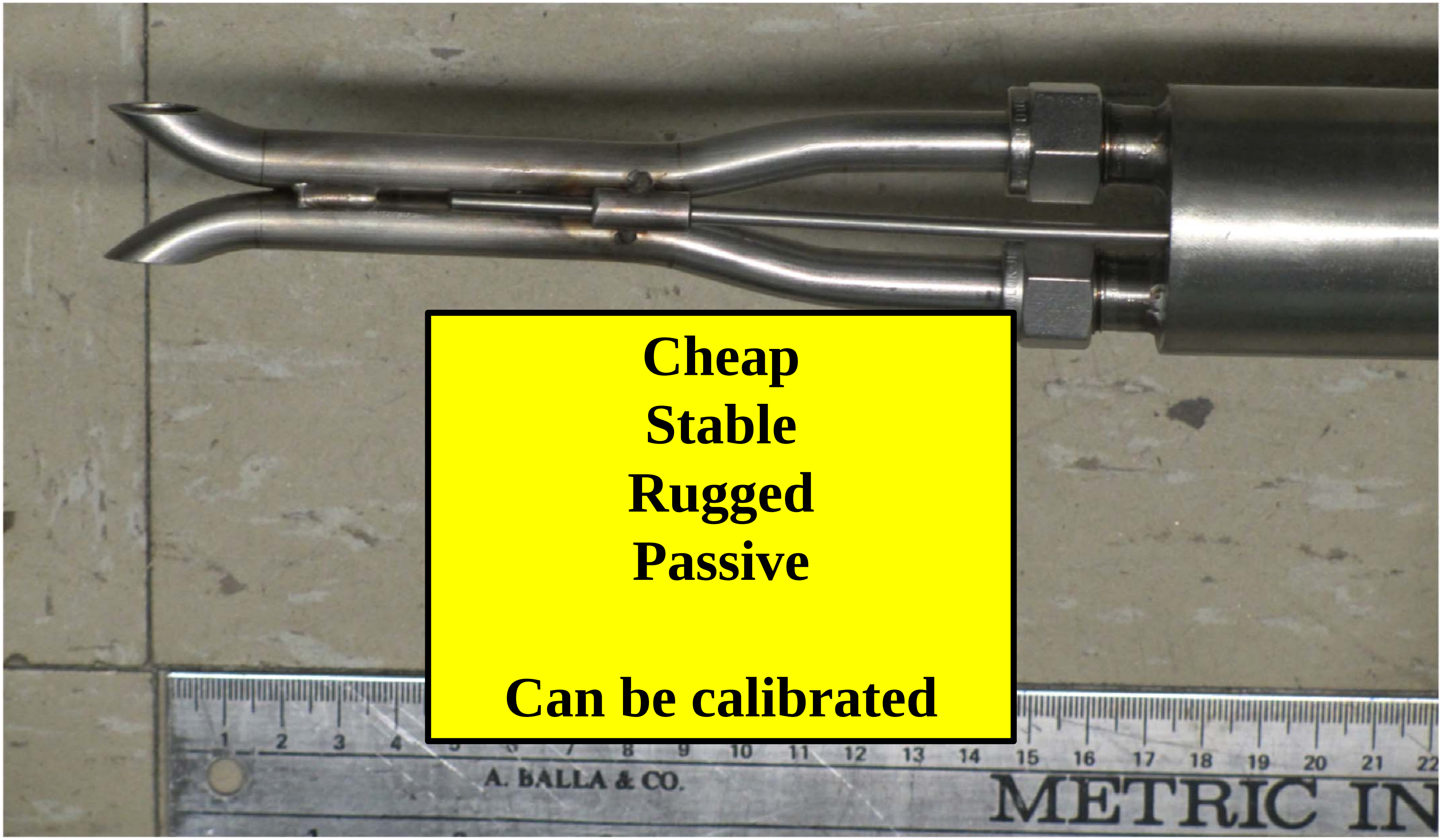
- **Measurement Problems**
  1) Profile Errors – USM measures *path velocity*, and not the area weighted velocity
  2) Swirl Errors – measured path velocity (V_L) includes contributions **both** from the axial and non-axial (*i.e.,* swirl) velocity components
  3) Installation Errors – depending on installation angle the acoustic path interrogates a different portion of flow field
- USM Calibrated by RATA

S-Probe: Workhorse for stack flow measurements

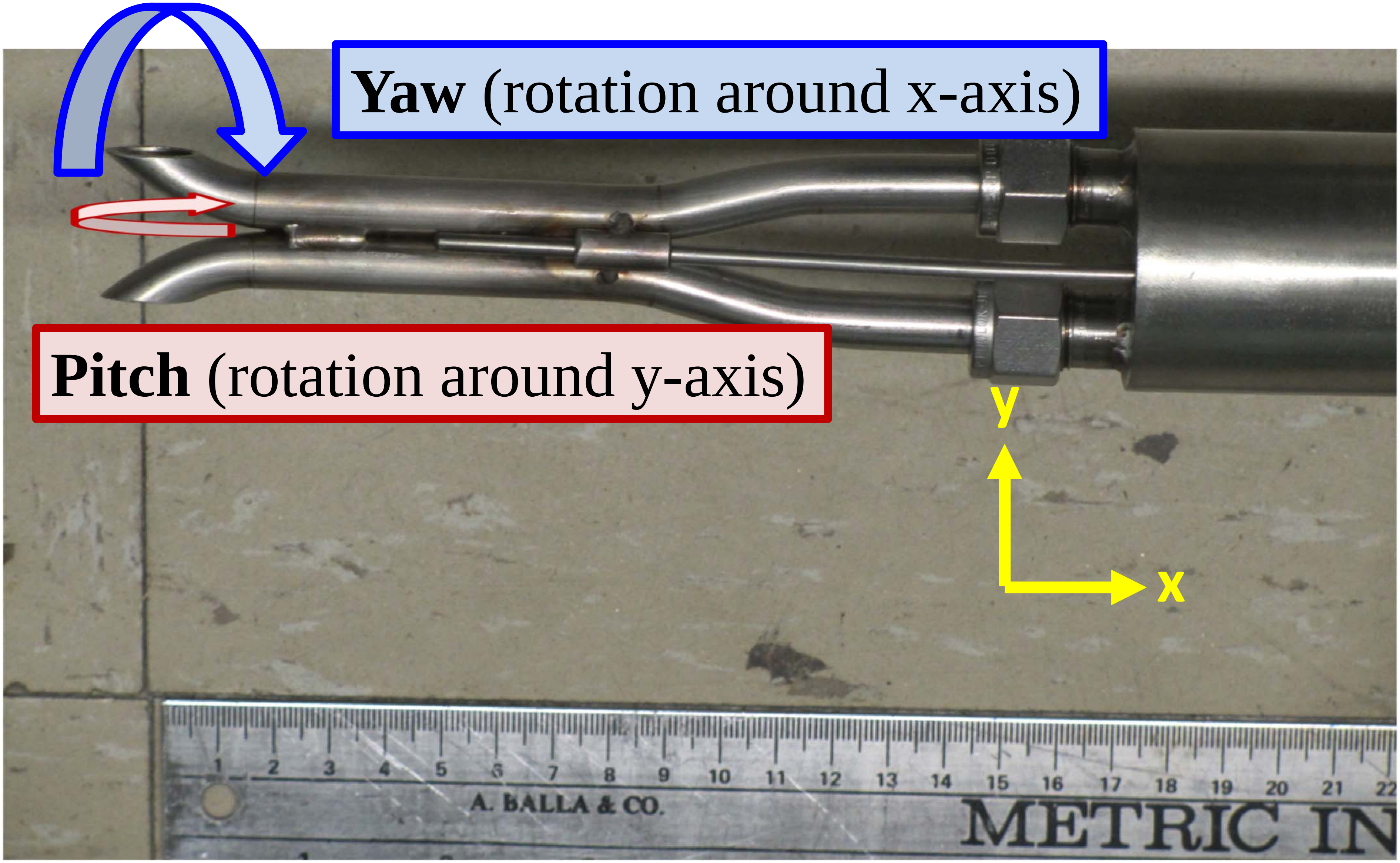
(Device used to "*calibrate*" the USM via the EPA RATA)



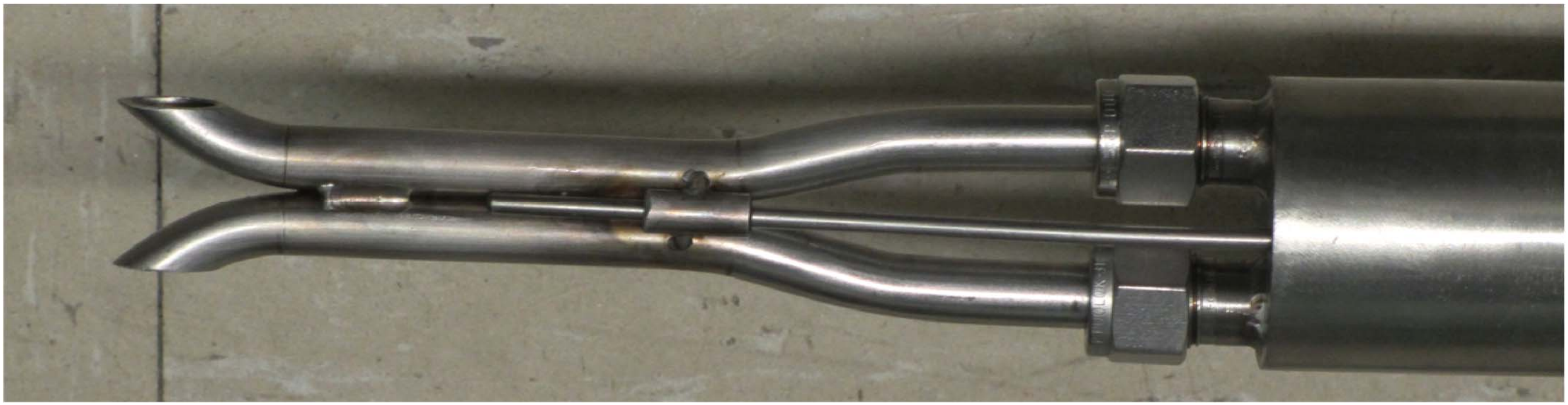
S-Probe: Workhorse for stack flow measurements

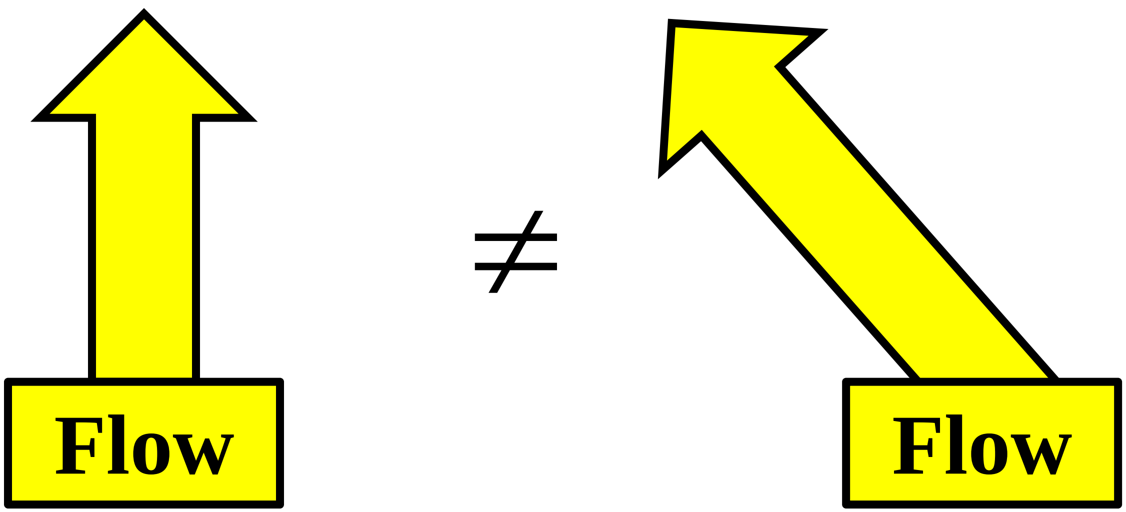


S-Probe: Geometric Calibration Parameters

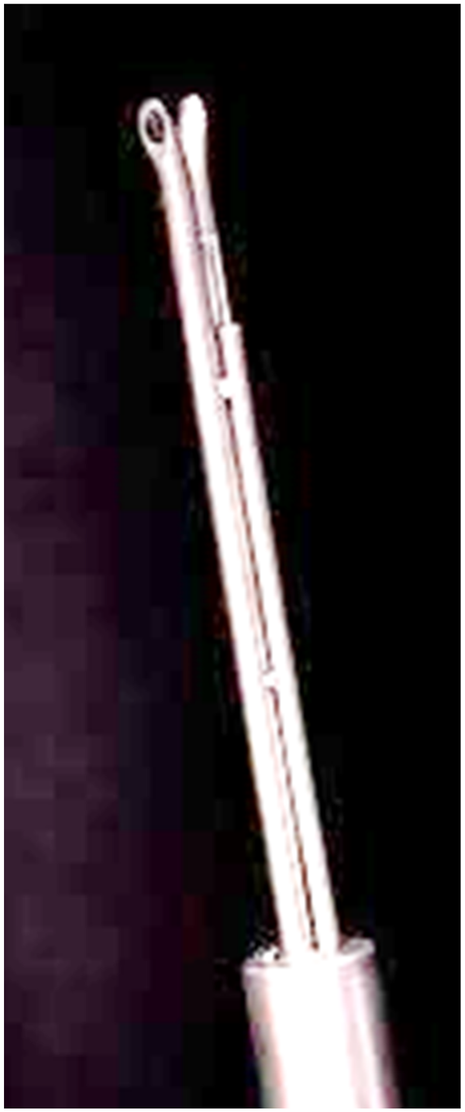


S-Probe: cannot detect pitch





S-Probe Calibration



Calibration Factor is a Function of 4 variables

1. Reynolds Number (Air speed)
2. Pitch angle (S-probe does not measure pitch)
3. Yaw angle
4. Turbulence intensity

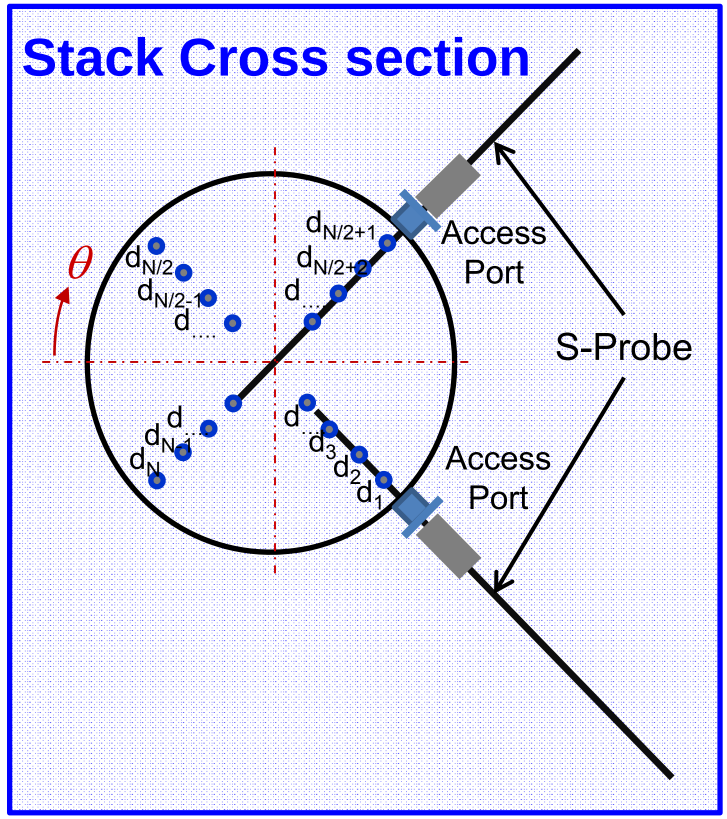
EPA protocol assumes calibration factor = 0.84

- The calibration factor **exhibits Reynolds number dependence** (*i.e.*, 4 % change with Reynolds number)
- Using the EPA calibration factor = 0.84 introduces **errors as large as 10%** depending for large pitch angles (pitch > 30° or pitch < -30°)

EPA Protocol to "Calibrate" CEMS using S-Probe

(Relative Accuracy Test Audit or RATA)

- S-Probe measures the fluid velocity at a point
- The S-Probe is traversed along two diameters in stack cross section
- Measured point velocities are integrated to determine the ***average flow velocity***
- RATA Protocol Based on EPA Documents
  - 40 CFR Part 60
  - 40 CFR Part 75 (2F, 2G, 2H)
- Measurement Problems
  - S-Probe often not calibrated (an assumed calibration factor = 0.84 is used)
  - S-Probes do not detect pitch
  - Velocity measured only along two diameters
  - Integration errors



What is NIST Doing?

1) **Tie EPA-CEMS instruments and protocols to primary standards (*Essential for International Recognition*)**
   A. Calibrate Pitot probes under realistic conditions (NIST Wind Tunnel)
   B. Determine accuracy of ultrasonic flow meters (USM) and S-Probes in complex *smokestack-like* flows (Newly Built Scale-Model Smokestack Simulator)
   C. Understand/model results to generalize and scale up (CFD)

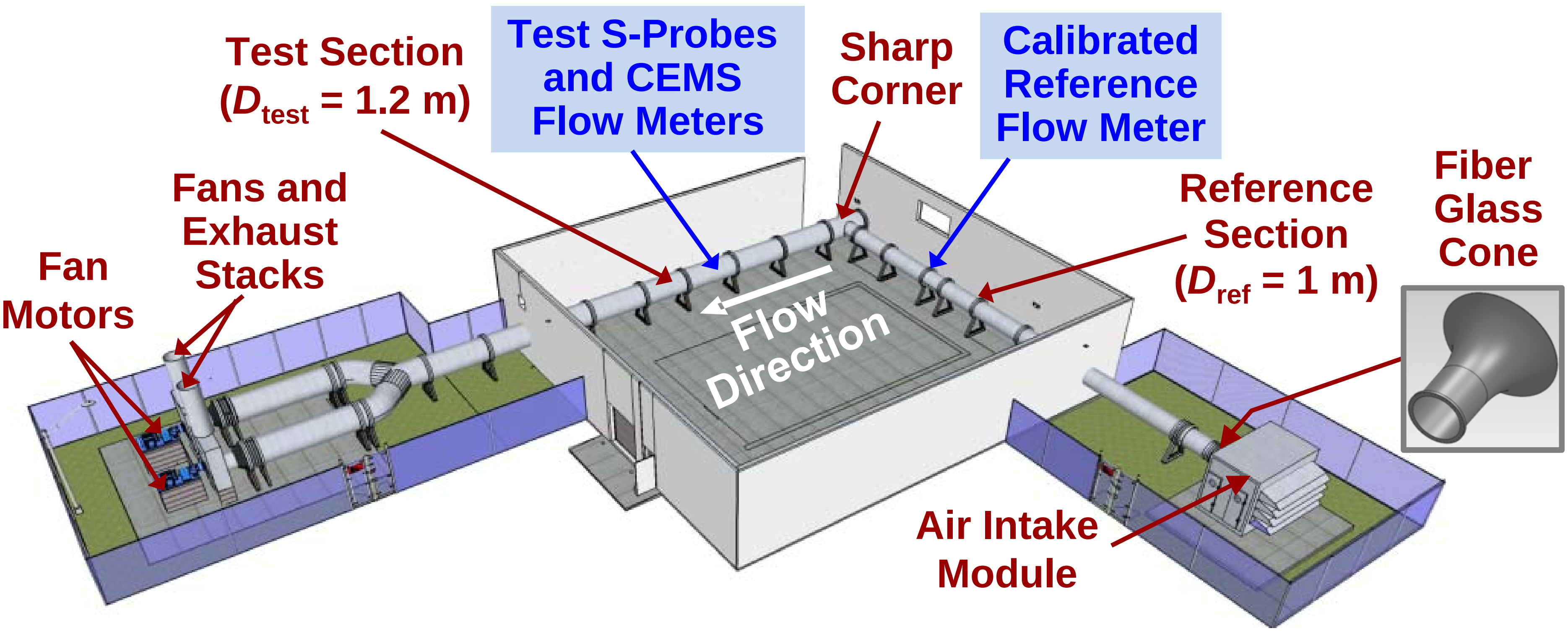
2) **Invent alternative flow standards for flue gas stacks (*to check entire measurement chain*)**
   A. Advanced Multipath Ultrasonic Flow Meters
   B. Long Wavelength Acoustic Flow Meter (LWAF)
   C. Tracer Dilution

3) **Test accuracy of 1) and 2) in a near-scale industrial smokestack** (Newly Built National Fire Research Laboratory)

NIST's Scale-Model Smokestack Simulator (SMSS)

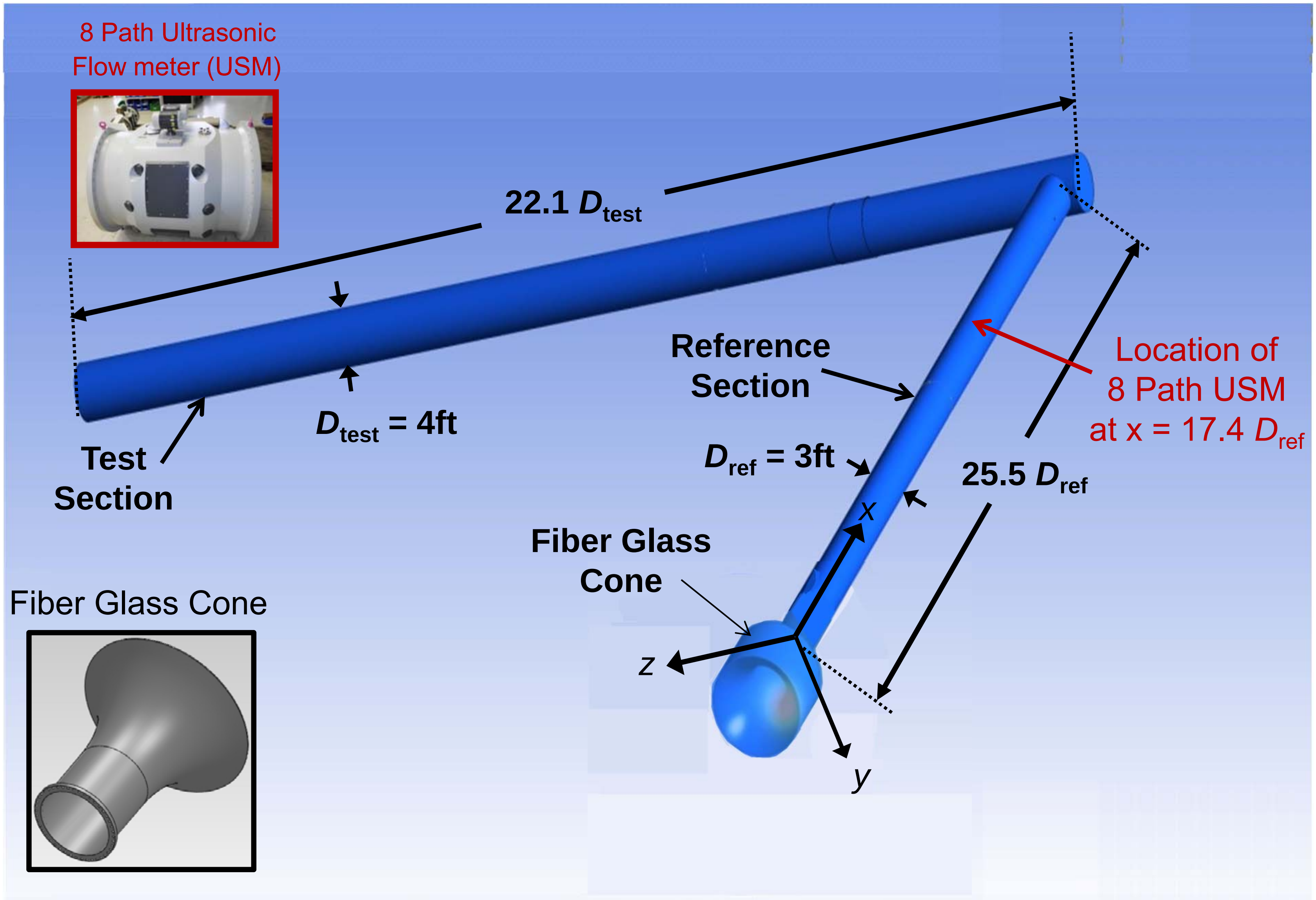
- Horizontal orientation for cost and safety
- SMSS is 1/10th the diameter of an industrial smokestack
- Air used as a surrogate for flue exhaust

Scale-Model Smokestack Simulator (SMSS)



- Ambient air is drawn into the Intake Module by the 2 fans at the exit
- **Reference Section:**
  - Designed to produce an ideal velocity profile with no swirl
  - SI Traceable flow measurement via NIST calibrated flow meter
- **Test Section:**
  - Flow velocities range from 6 m/s to 26 m/s (*same as industrial smokestacks*)
  - Sharp corner generates turbulent, skewed, swirling flows
  - CEMS and S-Probes evaluated in smokestack-like flow conditions

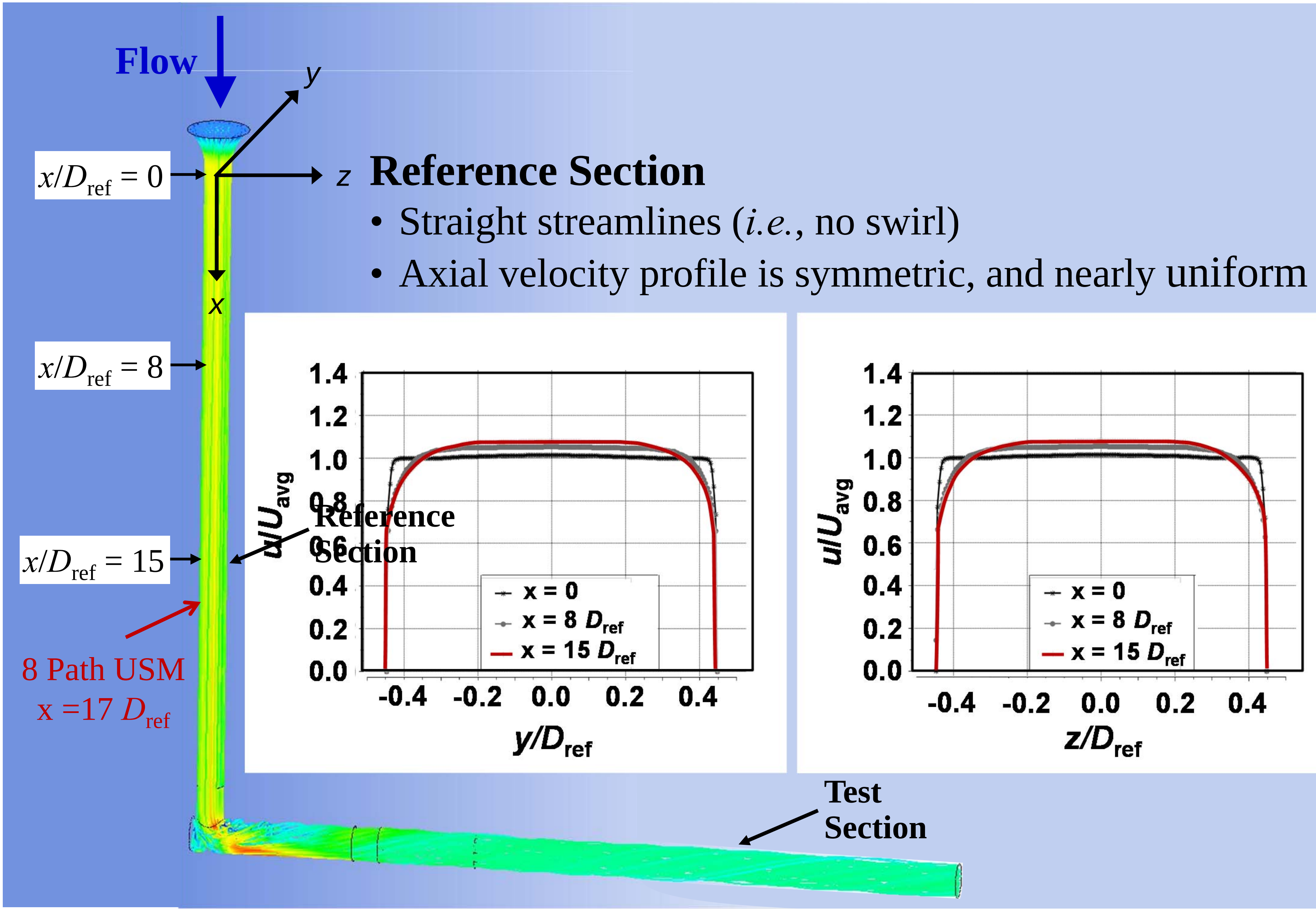
Computational Domain for Modeling SMSS



SMSS CFD Model

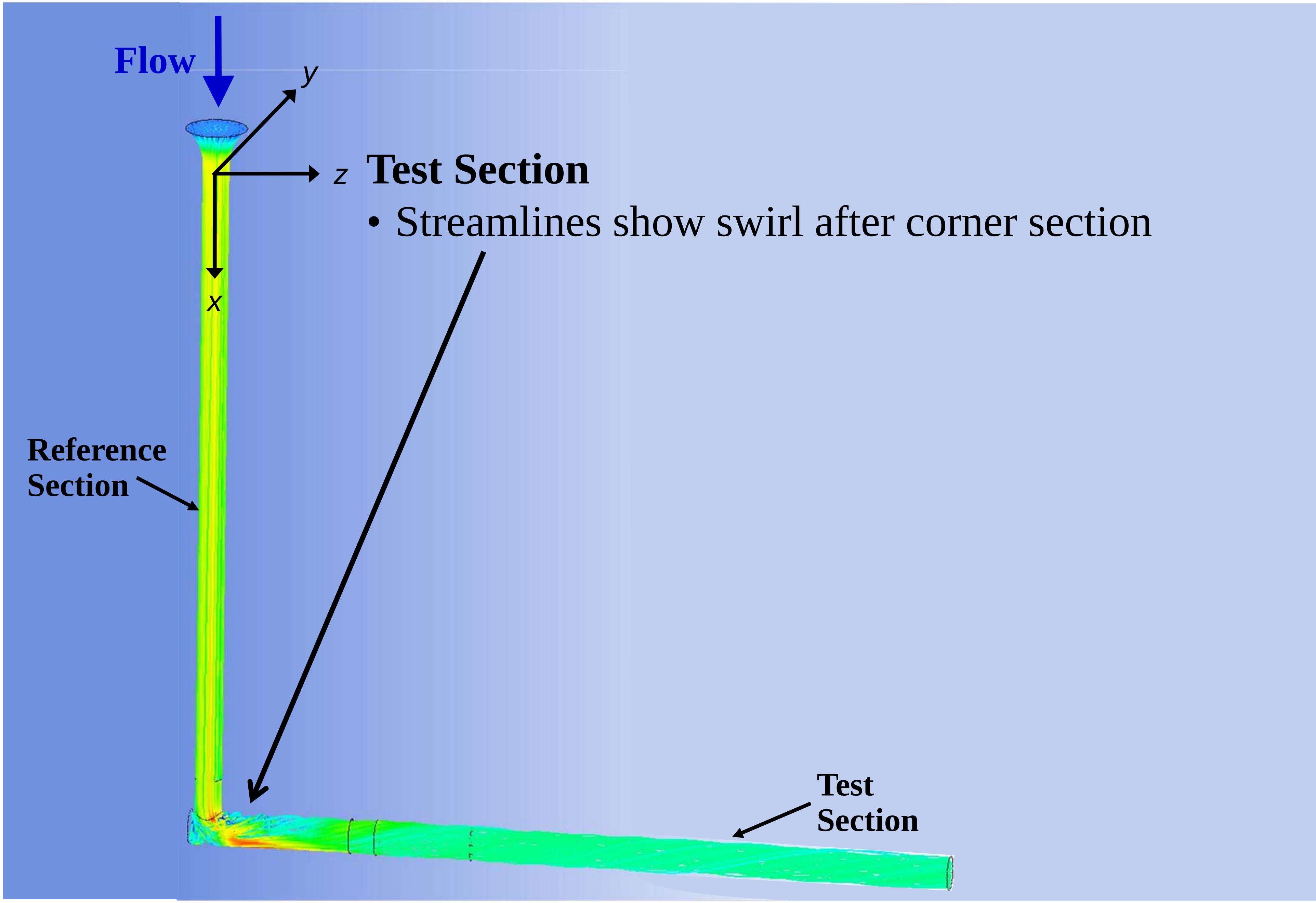
- **Used Commercial Code ANSYS FLUENT**
- **3D Steady, incompressible Reynolds Averaged Navier-Stokes Equations**
- **Turbulence Model**
  - Realizable k-ε turbulence model with enhanced wall functions
- **Fluid Properties**
  - Air at constant temperature
  - Density; ρ=1.225 kg/m^3,
  - Molecular Viscosity; μ=1.7894x10^{-5} kg/m·s
- **Boundary Conditions**
  - No slip at walls
  - Inlet Pressure at Spherical Volume: P = 101,325 Pa (absolute)
  - Outlet Pressure: P = -2000 Pa (gauge)
- **Numerical Scheme**
  - Solved using double precision,
  - **1st order spatial discretization**
  - Converged residuals on order of 10^{-3} or less
- **Mesh**
  - Unstructured with 9,800,000 cells

CFD Model



Flow
y
z
x
x/Dref = 0
x/Dref = 8
x/Dref = 15
Reference Section
• Straight streamlines (i.e., no swirl)
• Axial velocity profile is symmetric, and nearly uniform
Reference Section
8 Path USM
x =17 Dref
Test Section
u/Uavg
y/Dref
z/Dref
x = 0
x = 8 Dref
x = 15 Dref
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.4
-0.2
0.0
0.2
0.4

CFD Model



Test Section

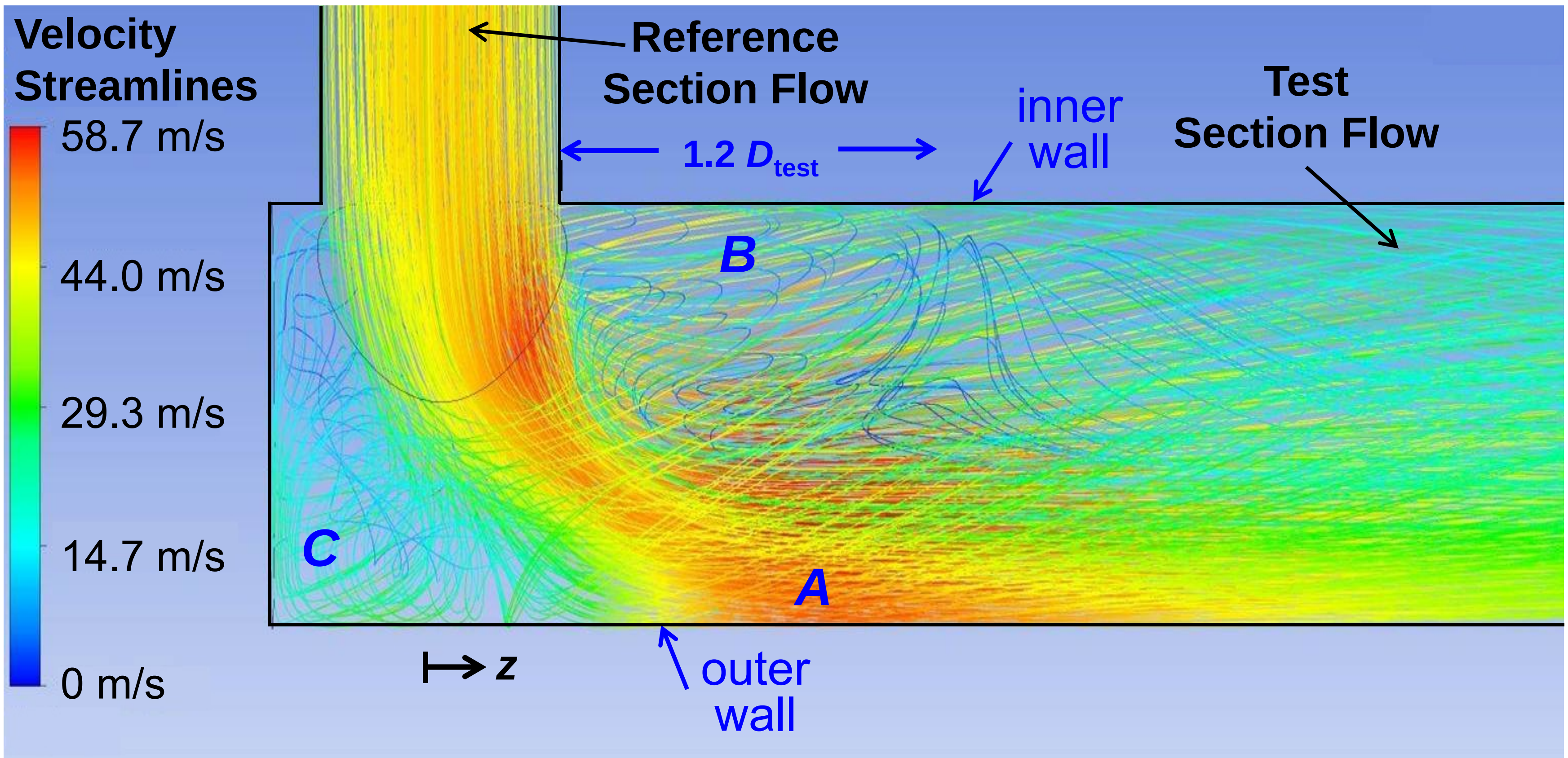
- Streamlines show swirl after corner section

CFD Model

(Flow just after corner in Test Section)

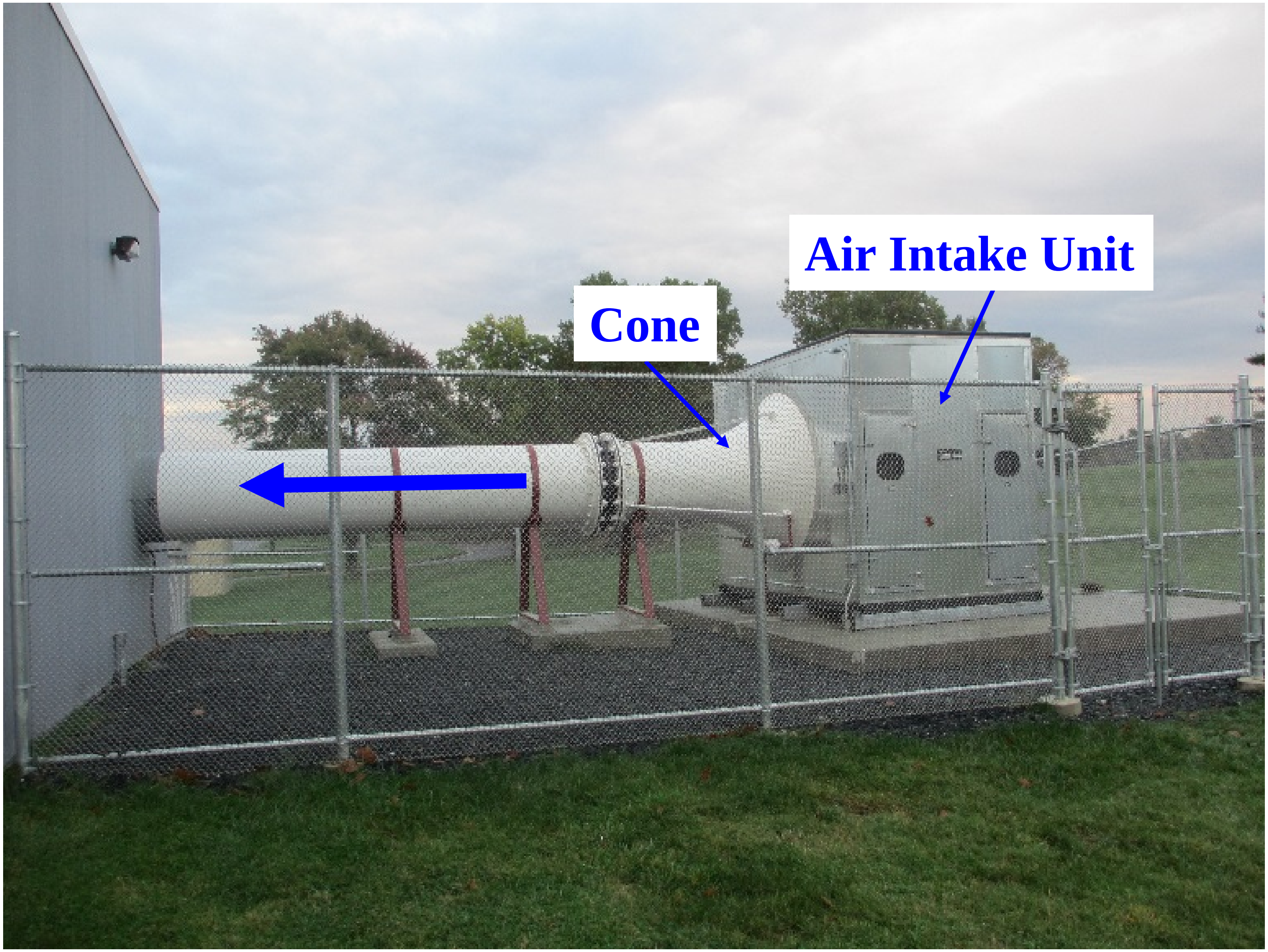
Test Section

- Streamlines show swirl after corner section
- Faster moving flow toward outer wall in Region A
- Reverse flow near inner wall in Region B
- Recirculation Zone in Region C

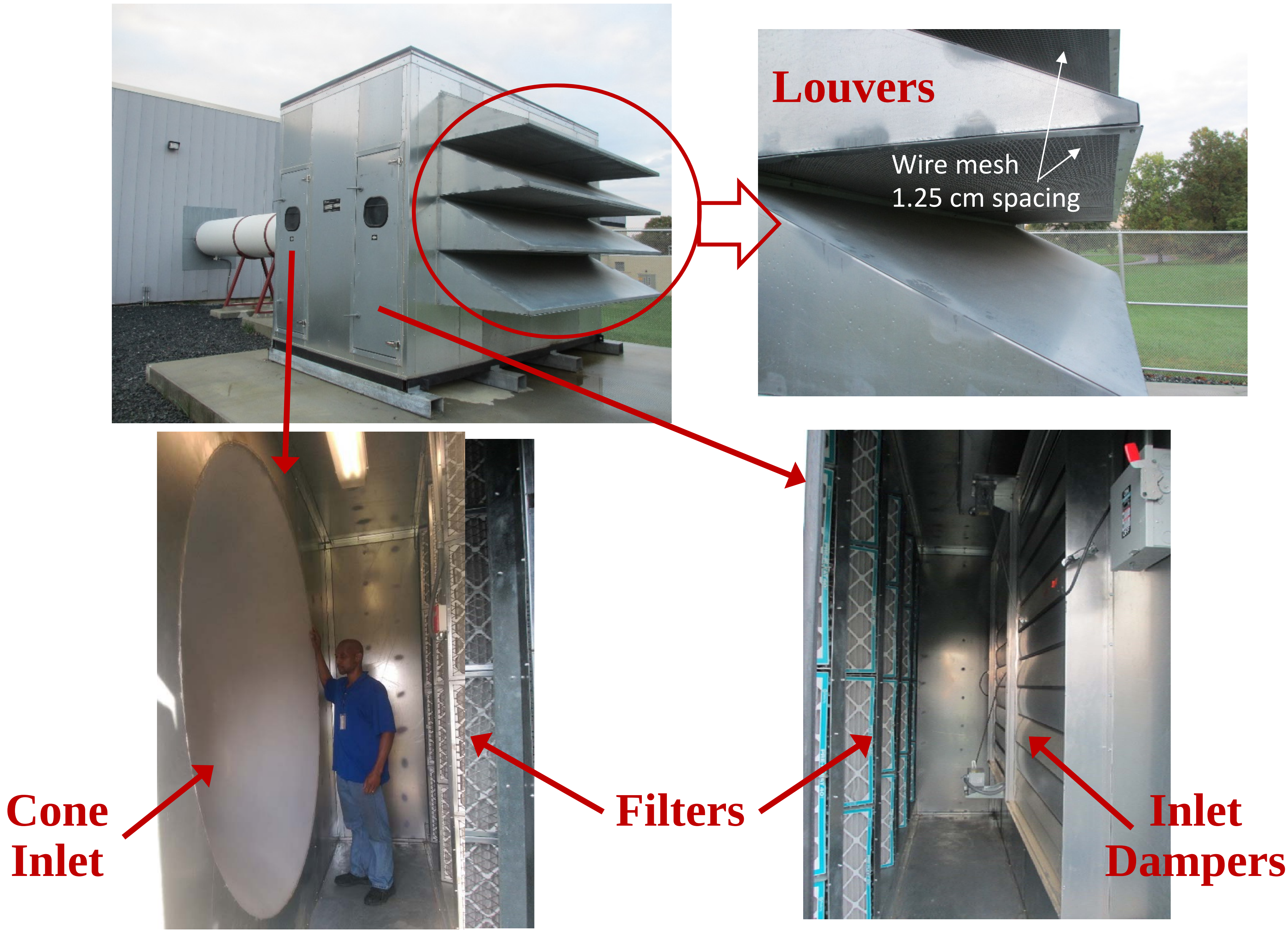


Scale-Model Smokestack Simulator (SMSS)

Air Intake Unit and Cone

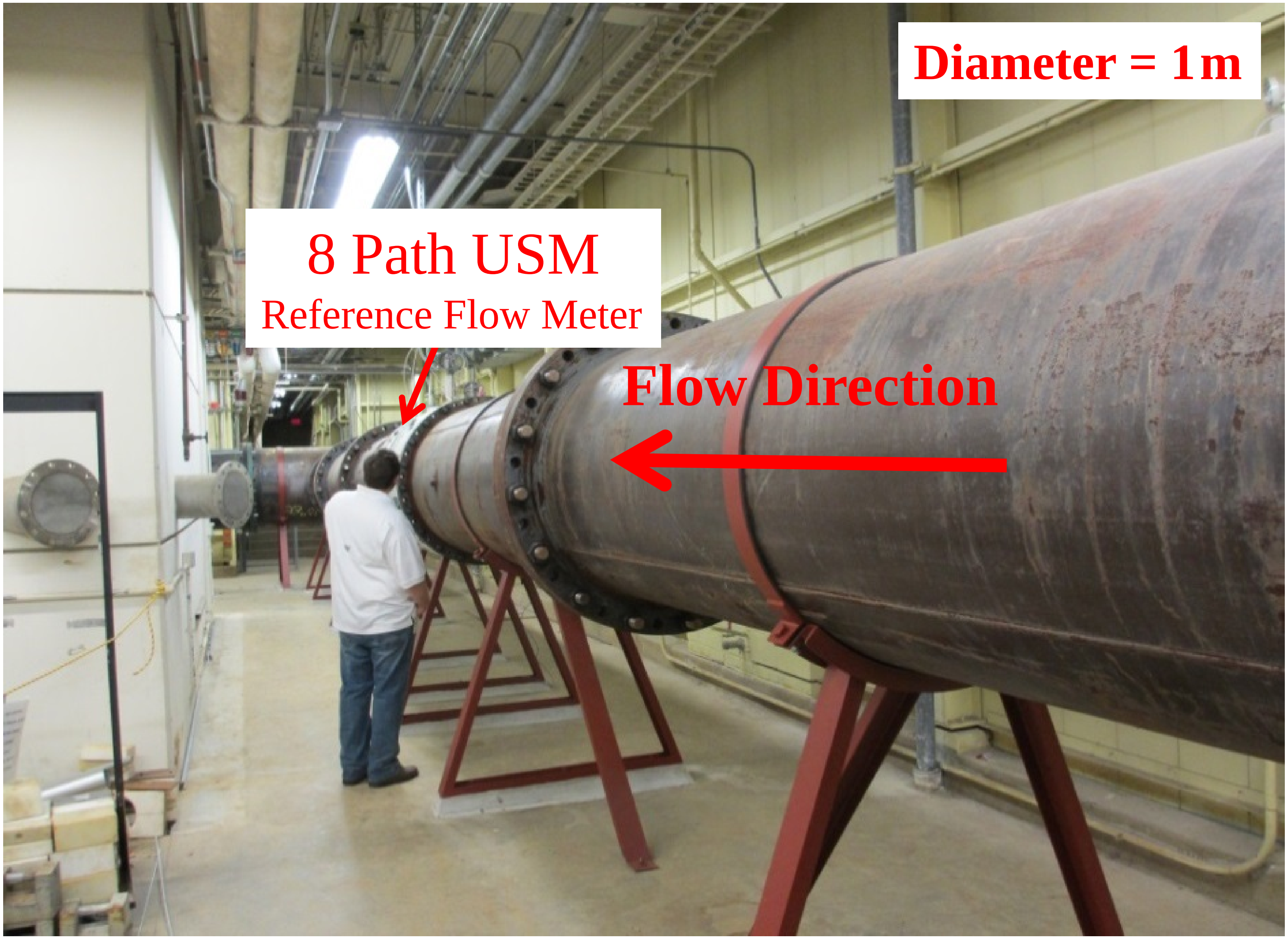


Air Intake Unit



Reference Section

(SI Traceable Flow Measurement)



SMSS Reference Flow Meter

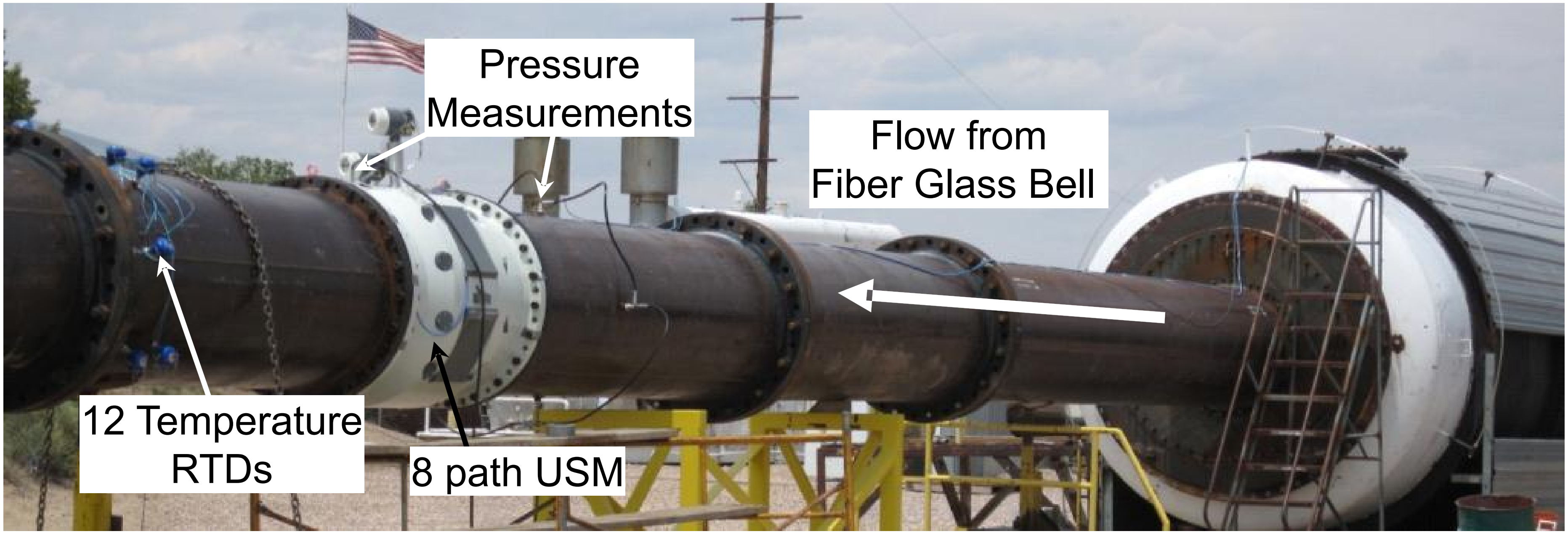
8 Path ultrasonic meter (USM)

Installed after 17 D of straight pipe (good flow)

Calibrated against NIST flow standards

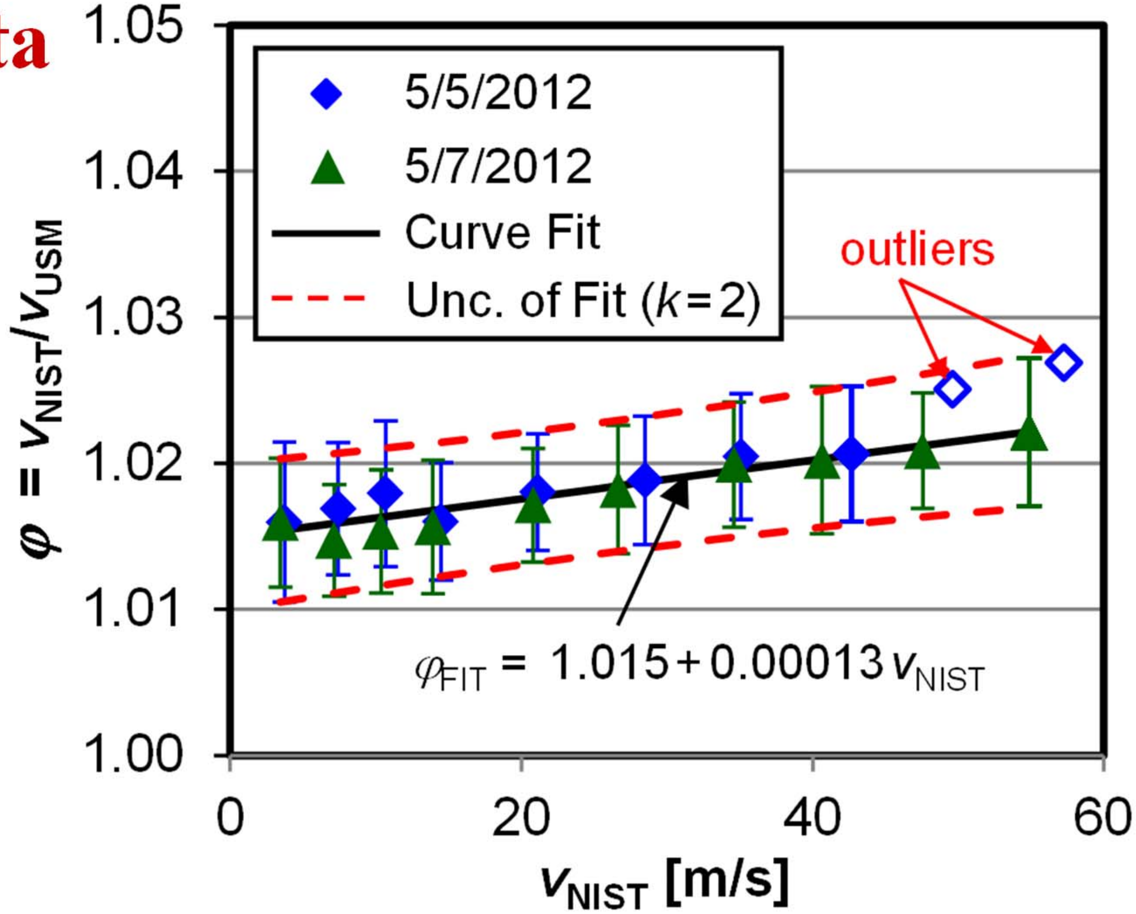
Determines bulk flow to 0.5%

Calibration of USM at CEESI in Colorado against NIST working standards



$$\varphi = \frac{V_{\mathrm{NIST}}}{V_{\mathrm{USM}}}$$ **Calibration Factor**

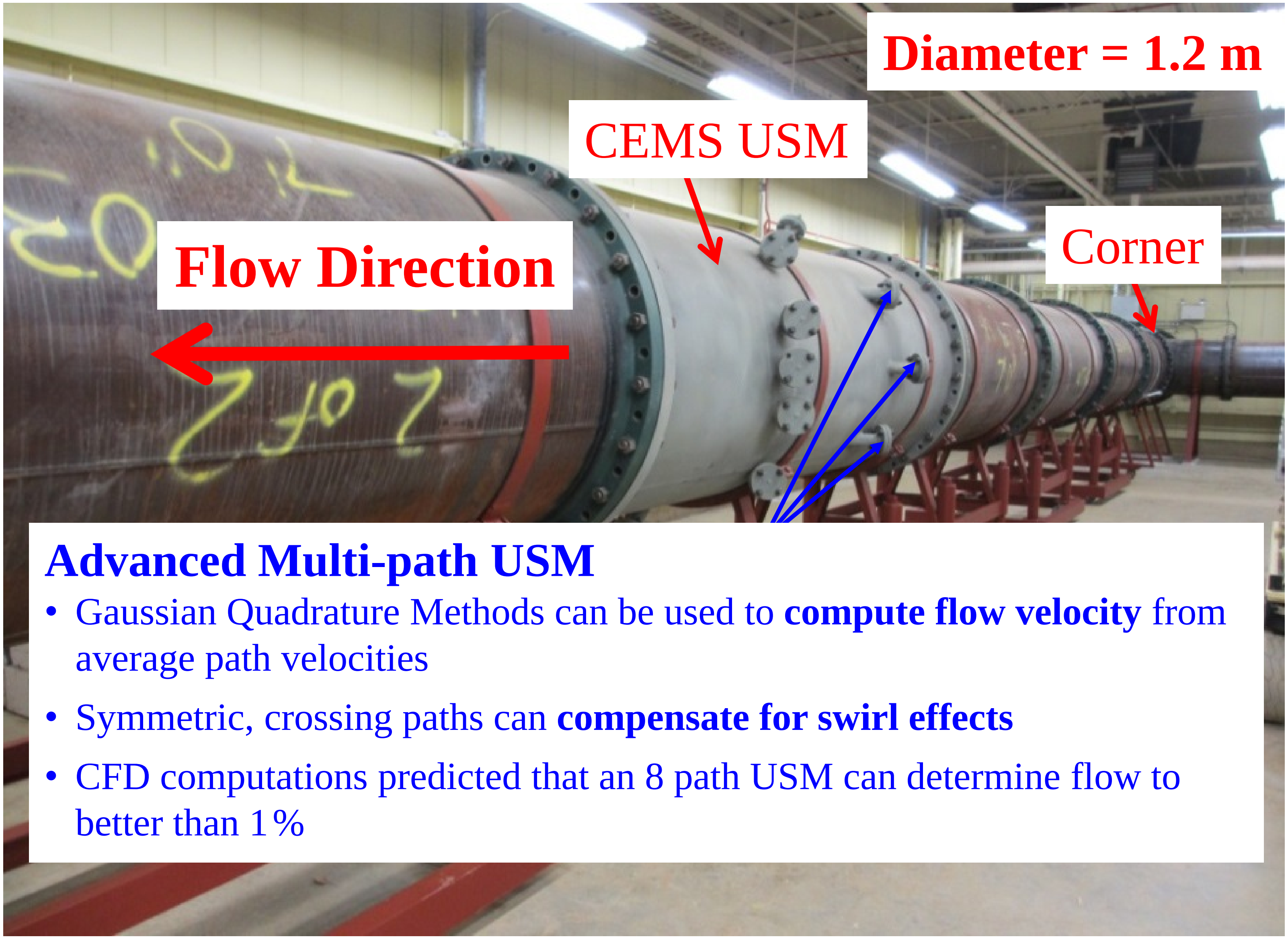
Calibration Data



- **Excellent Reproducibility < 0.075 %**
- **Expanded Uncertainty: 0.45 % to 0.58 %**
- **Best-ever calibration in air in this size**

Test Section

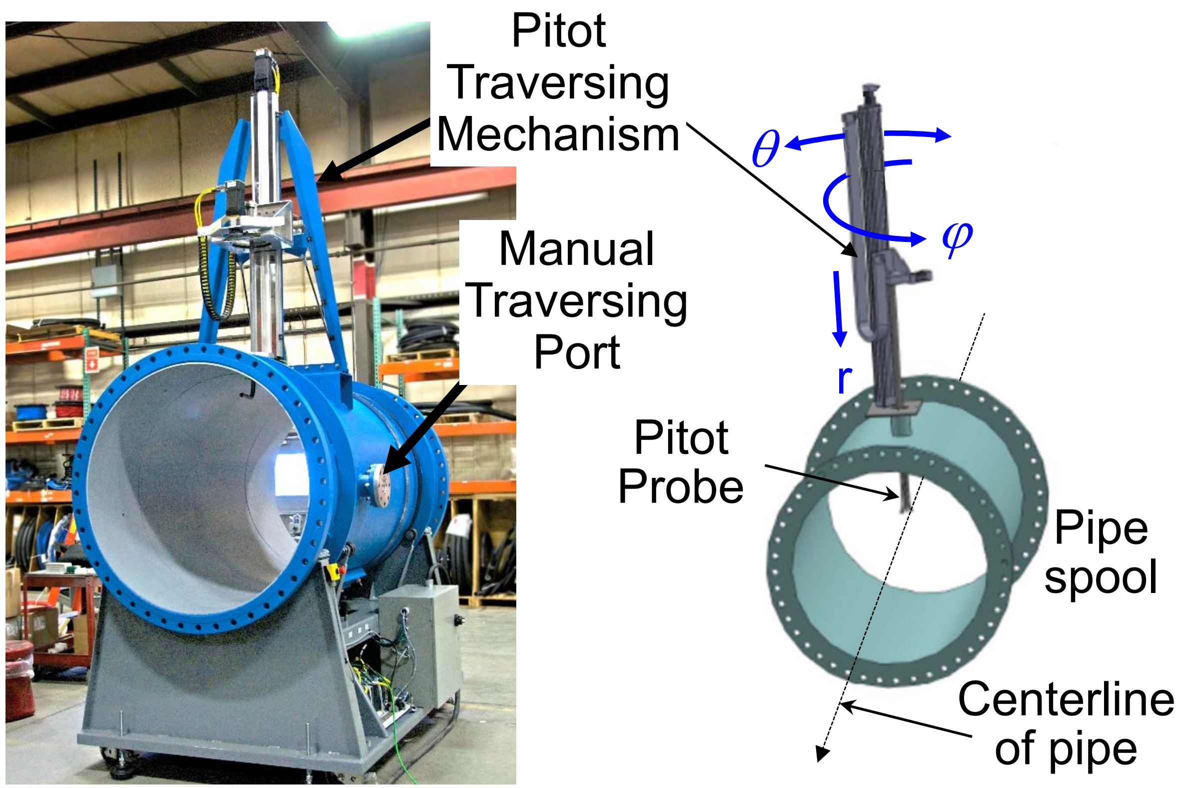
(Skewed, Swirling, Turbulent Flow)



Advanced Multi-path USM

- Gaussian Quadrature Methods can be used to **compute flow velocity** from average path velocities
- Symmetric, crossing paths can **compensate for swirl effects**
- CFD computations predicted that an 8 path USM can determine flow to better than 1%

Three Axis Automated Pitot Traversing Unit



Traversing Axis	Maximum Range of Motion	Expanded Uncertainty
r	1.2 m	< 0.5 mm
θ	200°	< 1°
φ	360°	< 0.5°

Research Plans

- Determine the in-situ performance and uncertainty of smokestack flow measurement technologies in swirling flows with skewed velocities
  - EPA RATA using S-Probe (and other types of pitot probes)
  - CEMS flow meters (Ultrasonic Flow Meters)

- Research and develop alternative approaches for smokestack flow measurements
  - Long Wavelength Acoustic Flow Meter
  - Multi-chord pitot traverse methods with advanced integration techniques
  - Advanced Multi-path ultrasonic flow meters
  - Differential absorption LIDAR
  - Tracer Dilution Methods

- Develop benchmark data to validate CFD (Computational Fluid Dynamic) models used for scale-up to full sized smokestacks

- Proficiency Testing (Facility for RATA testers to prove their capabilities)

Questions?